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Post-drainage peatland moisture and aeration dynamics.

by

Uldis Silins ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Department of Renewable Resources

Edmonton, Alberta

Spring 1997

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Post-drainage peatland moisture and aeration dynamics submitted by Uldis Silins in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Abstract

The purpose of this research was to evaluate the effects of forest drainage and subsequent subsidence on peat pore properties that govern soil moisture and aeration conditions important to tree growth. Changes to soil moisture and aeration conditions resulting from post-drainage subsidence were investigated at two peatlands drained for forestry near Saulteaux River, and Wolf Creek, Alberta.

Subsidence was associated with increased peat bulk density and degree of decomposition after drainage of both peatlands. These changes corresponded to a loss of pore sizes greater than 600 μm dia., and a concurrent increase in pore sizes between 3-30 μm dia. Mean soil water retention at soil water potentials spanning -5 to -15000 cm head was increased in drained areas by 20-300% over that of undrained areas. Relative differences in water retention were proportional to differences in bulk density between drainage conditions. Mean saturated hydraulic conductivity in drained areas was 1.69 cm/h compared to 14.46 cm/h in undrained areas. Conversely, unsaturated hydraulic conductivity in drained areas was greater than that in undrained areas at water potentials between -5 and -15000 cm head. Subsidence increased both the volume and transport rate of soil water in the range of soil water potentials available for use by trees.

Increased water retention in drained areas decreased the air-filled pore space important in soil aeration by 30-200% over that of undrained areas at Saulteaux River and Wolf Creek. However, this reduction in air-filled pore space did not result in decreased aeration of surface peat in drained areas of either peatland. Oxygen transport rates and O_2 concentrations were consistently greater, and the aerated zone extended 10-40 cm deeper in drained areas due to much lower water table levels compared to undrained areas. However, subsidence reduced aeration response of deeper soil layers to water table fluctuation by increasing the thickness of the capillary zone above the water table by 10-20 cm over that evident in undrained areas. Consistent with spatial patterns for water table drawdown, oxygen transport rates and depth of the aerated zone did not vary among different ditch spacings, but were affected by proximity to drainage ditch edges. Overall, both soil moisture conditions and aeration were improved for tree growth by drainage and subsequent subsidence.

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θ_v	water content (fractional volume, or % total volume basis)
θ_s	saturated water content (fractional volume)
θ_r	residual water content (fractional volume)
h	hydraulic head (cm)
α	empirical hydrologic parameter (cm^{-1})
n	empirical hydrologic parameter
λ	empirical hydrologic parameter
K_s	saturated hydraulic conductivity (cm/h)
K	unsaturated hydraulic conductivity (x 10^{-4} cm/h)
f_a	air-filled porosity (fractional volume, or % total volume basis)
ODR	oxygen diffusion rate (x 10^{-8} g cm^{-2} min^{-1})

1 Chapter One

General introduction

Peatlands develop in regions where cool climatic conditions interact with ground, or surface water to create conditions that restrict organic matter decomposition and lead to the accumulation of peat (Gore 1983). Peatlands are estimated to occupy roughly 500 million ha, or 3.8 % of the global land surface (Paavilainen and Päivänen 1995). Though these communities vary in landform and species composition world-wide, the presence of near-surface water is a keystone component of all peatlands. Variation in regional and local hydrology is the dominant ecological force which has led to the rich diversity of peatland landforms and the communities they support (Ingram 1983).

Peatland resources have been used by man throughout history. These uses often involved modifying the hydrology of peatlands to aid in harvest of the resource, or to improve conditions for its production. Examples of early peatland drainage for agriculture pre-date the Roman empire (Paavilainen and Päivänen 1995). In contrast, water control measures have more recently been used to regenerate degraded, or mined peatlands (Grootjans *et al.* 1992). In both cases, alteration of hydrologic conditions by man results in ecological changes that modify the site from its undisturbed, or present state. Some of these changes are purposefully intended while others may be unintentional, or at least, less well understood. It is on some ecological changes of the latter type that this thesis is focused.

1.1 PEATLAND FORESTRY

In Canada, peatlands are conservatively estimated (Paavilainen and Päivänen 1995) to constitute 25.6 % of the forested landbase (Haavisto and Jeglum 1991). Alberta contains approximately 12.7 million ha of peatlands which comprise 36.3% of forested lands (Tarnocai 1984). Much of this area supports black spruce (*Picea mariana* (Mill.) B.S.P.) and tamarack (*Larix laricina* (Du Roi) K. Koch.), however poor tree growth combined with difficult operating conditions have limited utilization and management of these forested peatlands.

Tree growth in unmanaged peatlands is generally poor compared to upland forests due to unfavorable rooting conditions created by persistently

high ground water table levels (Dang and Lieffers 1989, Lieffers and Macdonald 1990). Unfavorable soil moisture (Macdonald and Lieffers 1990, Dang *et al.* 1991), aeration (Boggie 1977, Lähde 1969, Mannerkoski 1985), temperature (Lieffers and Rothwell 1987), and nutrient conditions for tree growth (Macdonald and Lieffers 1990, Lieffers and Macdonald 1990, Mugasha *et al.* 1993) are all characteristic of water saturated peat soils. These conditions restrict tree roots to shallow, unsaturated surface layers further compounding poor water and nutrient relations in peatland trees (Kozlowski 1982).

Forest drainage has been used to improve peatlands for tree growth in northern Europe since the mid-nineteenth century (Paavilainen and Päivänen 1995). In Alberta, several experimental drainage trials were established during the latter part of the 1980's (Hillman 1987). Though forest sector interest in operational drainage has not yet developed in this province, recent expansion of Alberta's forest industry has resulted in near-full allocation of the productive forest landbase. As a consequence, greater interest now exists in silvicultural practices that improve tree growth on both productive and unproductive forest lands than in the recent past. Application of forest drainage techniques to improve unproductive peatland sites will probably be given more serious consideration as timber supplies become increasingly restricted in Alberta.

The objective of forest drainage is to lower ground water table levels to improve rooting conditions for peatland trees. Lower water table levels after drainage improve soil moisture (Rothwell *et al.* 1996), aeration (Lähde 1969, Mannerkoski 1985), thermal (Lieffers and Rothwell 1987, Rothwell 1991), and nutrient conditions (Mugasha *et al.* 1993, Humphrey and Pluth 1996) for root growth. Early increases in growth of black spruce and tamarack after drainage in Alberta are associated with post-drainage changes in these soil conditions (Dang and Lieffers 1989, Rothwell and Silins 1990, Yin 1993). However, the long term growth response of peatland trees, and thus the economics of forest drainage practices remain unproven in this province. This uncertainty stems partially from the fact that soil conditions present shortly after drainage change over time. These changes are not easily predicted based on the magnitude of post-drainage water table lowering alone (Rothwell *et al.* 1996) as they involve complex interactions among many physical and biological factors. The temporal dynamics of these interactions, and their modifying effect on rooting conditions for tree growth are not well understood.

1.2 POST-DRAINAGE SUBSIDENCE

Subsidence, or a decrease in the surface elevation of peatlands is well documented after drainage, fertilization, and cultivation of peatlands for agriculture in Europe and Canada (Schothorst 1977, 1982, Mirza and Irwin 1964, Campbell and Millette 1981, Parent *et al.* 1982, Millette *et al.* 1982). Less, however, is known about subsidence in the comparatively undisturbed conditions characteristic of drainage for forestry. Physical settling and consolidation of peat soon after drainage, and accelerated organic matter decomposition over longer periods of time are considered to be the dominant mechanisms involved in subsidence (Paavilainen and Päivänen 1995).

Lukkala (1949) reports approximately 80-90% of total elevation loss (20-40 cm) 36 years after drainage of several Finnish peatlands occurred within the first 5-10 years. Rapid initial subsidence (elevation loss and increased peat bulk density) was also observed by Rothwell *et al.* (1996) after drainage of several forested peatlands in Alberta. Mean elevation loss was 3.9-11.0 cm 1-2 years after drainage, and mean bulk density of surface peat (0-30 cm depth) increased by 45-50% over that of undrained areas 2-3 years after drainage (Rothwell *et al.* 1996). Subsidence shortly after drainage appears related to the magnitude of water table lowering (Lukkala 1949, Rothwell *et al.* 1996). Variation in elevation loss and/or bulk density is associated with variation in mean water table levels among ditch spacings (Rothwell *et al.* 1996), and to water table "mounding", or variation in water table levels between adjacent ditches (Lukkala 1949, Rothwell *et al.* 1996).

Estimates of longer term subsidence due to organic matter oxidation are somewhat more speculative (Paavilainen and Päivänen 1995). Total elevation loss observed by Laine *et al.* (1994) in peatlands drained 60 years earlier was of similar magnitude to that reported by Lukkala (1946) 14-36 years after drainage. Increases in bulk density observed by Laiho and Laine (1992, 1994), and Laine *et al.* (1994) 41-60 years after drainage of several Finnish peatlands were also similar to those reported by Rothwell *et al.* (1996) 2-3 years after drainage. These observations support Lukkala's (1949) suggestion that most of the elevation loss occurs within 5-10 years of drainage. However, the relationship of long term subsidence with site conditions is unclear. Brække (1987) and Lukkala (1949) reports greater subsidence after drainage of

ombrotrophic peatlands compared to fen peats, while Laine *et al.* (1994), and Laiho and Laine (1992) report greater subsidence after drainage of more minerotrophic and nutrient rich peatland types. Laine *et al.* (1992) observed no clear pattern of elevation loss 60 years after drainage along a minerotrophic - nutrient gradient.

Though subsidence can be considered as part of overall drainage effects on forested peatlands, the effects of increased bulk density due to subsidence may be quite different from those produced by water table lowering by drainage alone. Lower water table levels after drainage reduce soil water content by emptying water filled soil pores in proportion to the water potential gradient created by drainage (Päivänen 1973). Post-drainage soil water content is therefore dependent on both the water potential gradient created by lower water table levels and the water retention characteristics of the soil. Bulk density is closely associated with peat pore size distribution and soil water retention (Boelter 1964, 1969, Päivänen 1973). Humified peats with greater bulk density have smaller mean pore sizes, and retain more water at equivalent water potentials (other than at saturation) than less decomposed, low bulk density peat (Boelter 1964, 1969, Päivänen 1973). Therefore, increased bulk density due to subsidence can increase soil water contents beyond those established by water table lowering through drainage. Rothwell *et al.* (1996) reported greater soil water contents near ditch edges where water tables were deepest. Elevation loss and increased bulk density due to subsidence was also greatest at these locations. Pore size distribution also regulates saturated and unsaturated hydraulic conductivity (Hillel 1980). Though not reported after forest drainage, greater bulk density after subsidence would probably also result in altered drainage characteristics (Boelter 1972), and unsaturated capillary transport of water (Päivänen 1973).

Changes in bulk density due to subsidence may have effects on peat soils that extend beyond modification of soil moisture conditions. Soil water content largely governs aeration, as gas exchange between the soil and atmosphere occurs primarily by diffusion through air filled soil pores (Glinski and Stepniewski 1985). The volume of air filled pores is inversely proportional to the volume of water filled pores (Hillel 1980). Increased soil water contents due to subsidence could potentially reduce air filled porosity and restrict soil aeration. Soil water content also regulates peatland thermal regimes by altering

soil heat capacity and thermal conductivity (Lieffers and Rothwell 1987, Rothwell 1991). The interaction of soil moisture, aeration, and thermal conditions, in turn, regulate organic matter decomposition (Lähde 1969, Lieffers 1988) and peatland nutrient mineralization (Williams 1974, Humphrey and Pluth 1996).

Several authors have suggested increased peat bulk density due to subsidence is involved in changes to peat soil moisture (Rothwell *et al.* 1996), aeration (Lähde 1974) and nutrient conditions (Humphrey and Pluth 1996, Laiho and Laine 1992, 1994) after forest drainage. However, the physical and biological mechanisms involved in these changes are not well understood. Aside from recent Fennoscandinavian research into long term peatland carbon and nutrient stores (Laiho and Laine 1995, 1994, 1992, Laine *et al.* 1992, 1994), surprisingly little research has been conducted on the effects of subsidence on soil conditions in forested peatlands. These soil conditions regulate tree growth, therefore understanding these changes is important in evaluating the long term productivity of peatlands drained for forestry. In addition, there is public concern about the long term effects of forest drainage on non-target peatland vegetation and wildlife in Alberta (Anon. 1993). Little information currently exists to address these issues.

1.3 OVERVIEW OF STUDIES

In order to understand how subsidence affects peatlands after drainage, a basic understanding of how soil pore characteristics are altered by subsidence, and how these changes modify the occurrence and transport of resources for plant growth is required. Though subsidence probably also involves changes to peat thermal energy relationships, nutrient conditions, and soil biota, my research was focused on the study of post-drainage soil moisture and aeration conditions. The overall objectives of my research were to examine the effects of altered peat bulk density on soil pore characteristics and how these, in turn, modify the interaction between soil water and oxygen conditions after forest drainage.

As consolidation of peat soils due to subsidence may take several years to develop, I adopted a retrospective approach by studying two peatlands drained for forestry in 1984 and 1987. The relationship of soil pore characteristics with soil moisture and aeration conditions in the drained areas

were compared to conditions present in adjacent undrained areas of the peatland. This approach is based on the assumption that the peat and vegetation characteristics of drained and undrained areas were similar before drainage.

In the study reported in Chapter Two, I explored the relationship between post-drainage increases in peat bulk density with soil moisture retention and transport characteristics. In this study, I examined the magnitude of subsidence effects on soil moisture properties 6 years after drainage of a forested peatland in Alberta. Subsidence effects on bulk density, degree of decomposition, pore size distribution, soil water retention, and saturated and unsaturated hydraulic conductivity were studied.

The effect of altered soil moisture conditions due to subsidence on aeration was examined in a field study conducted at peatlands near Saulteaux River and Wolf Creek, and is reported on in Chapter Three. In this study, the interaction of post-drainage water table levels with altered soil pore water-air volume relationships due to subsidence, and how these in turn, were related to soil oxygen concentrations, oxygen diffusion rates, and depth of soil aeration was explored.

Chapter Four describes results of a field study conducted at Saulteaux River and Wolf Creek that examined spatial variability of post-drainage soil aeration. Variation in subsidence and post-drainage water table levels among different ditch spacings, and between adjacent ditches on soil oxygen diffusion, and depth of aeration were studied.

A study that examined how subsidence effects on soil water retention influence black spruce seedling water relations was also conducted during the course of my thesis research. In that study, the effect of differential soil water potentials between peat from drained and undrained areas on black spruce seedling photosynthesis and water relations was examined. As the objectives of this study were divergent from the general theme common to Chapters Two, Three, and Four, results of this study were not included in this dissertation. The results of this work are, however, published as part of another study with co-authors; Dr. R.L. Rothwell and Dr. G.R. Hillman in the paper titled "The effects of drainage on soil water content at several forested Alberta peatlands" in the Canadian Journal of Forest Research January 1996.

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2 Chapter Two

The effect of post-drainage subsidence on peat water retention, and transport characteristics at a forested peatland in Alberta

In addition to improving soil aeration (Lähde 1969, Mannerkoski 1985), thermal (Rothwell 1991), and nutrient conditions (Humphrey and Pluth 1996, Laiho and Laine 1992, 1994) for tree growth, drainage can also lead to subsidence, or a reduction in surface elevation of peatlands (Brække 1983, Laine *et al.* 1992, 1994, Lukkala 1949, Rothwell *et al.* 1996). Post-drainage subsidence results from physical settling, or consolidation of peat, and accelerated mineralization of organic matter (Egglesman 1972, Paavilainen and Päivänen 1995). Both of these processes increase peat bulk density after drainage (Laine *et al.* 1992, 1994, Laiho and Laine 1992, Rothwell *et al.* 1996). Bulk density is closely associated with the hydrologic properties of peat soils (Boelter 1964, 1969, Päivänen 1973) therefore, additional modification of soil moisture conditions, beyond the effects of lower water table levels due to drainage, are possible. The purpose of this study was to examine the effects of subsidence on soil moisture characteristics at a peatland drained for forestry in Alberta.

Peat bulk density is closely related to pore size distribution which regulates soil water retention as well as saturated and unsaturated water transport dynamics (Boelter 1964, 1969, 1972, Päivänen 1973). Contrary to general expectations, greater soil water contents have been reported after drainage compared to nearby undisturbed peatlands in Alberta (Humphrey and Pluth 1996, Rothwell *et al.* 1996). Greater post-drainage soil water contents observed by both authors were associated with greater peat bulk density after drainage. The greatest water contents reported by Rothwell *et al.* (1996) were observed near drainage ditches where water table levels were lowest. Elevation loss and increased bulk density due to subsidence were also greatest at these locations (Rothwell *et al.* 1996).

The relationship between peat bulk density, water retention, capillary moisture transport from the water table, and saturated hydraulic conductivity are known in general for peat of varying origin and degree of decomposition (Boelter 1964, Päivänen 1973). However, changes to pore properties governing these hydrologic characteristics have not, to my knowledge, been previously

reported after forest drainage. Greater post-drainage bulk density due to subsidence is not likely to be reversible, thus long term changes to vadose zone water dynamics are possible. Little is known about how soil pore characteristics are altered by subsidence, thus the magnitude of these hydrologic effects is currently speculative.

The objectives of this study were to determine the effects of subsidence on peat bulk density and pore size distribution and to examine how these changes, in turn, altered several important hydrologic characteristics within the rooting zone at one of Alberta's earliest forest drainage trials. Elevation benchmarks were not established before drainage of the Saulteaux River drainage trial (Tóth and Gillard 1988), thus the magnitude of post-drainage subsidence at this peatland was not known. However, differences in both peat decomposition and bulk density between drained and undrained areas of this peatland would provide strong evidence that subsidence occurred at the Saulteaux River drainage trial. I expected greater post-drainage peat bulk density previously observed at this peatland (Rothwell and Silins 1990, Rothwell *et al.* 1996) to be associated with greater degree of peat decomposition compared to peat from an undrained portion of the peatland. I expected water retention of drained peat to be greater, and mean pore size to be smaller than that of undrained peat from the same peatland, resulting in lower saturated hydraulic conductivity and altered unsaturated hydraulic conductivity relationships compared to undrained peat.

2.1 MATERIALS AND METHODS

The Saulteaux River peatland (55°8'N; 114°15'W) is situated in north central Alberta. The peatland is an intermediate fen supporting young, mixed stands of *Picea mariana* and *Larix laricina*. Understorey vegetation consists of *Betula pumila* and *Ledum groenlandicum*. Several *Carex* species are common on this site. Dominant mosses include *Sphagnum warnstorfii*, *S. fuscum*, *S. angustifolium*, *Tomenthypnum nitens*, *Aulacomnium palustre*, and *Drepanocladus* spp. Peat thickness within the study area ranges from 2-3 m. Mean annual precipitation at the Smith Ranger Station (approximately 10 km east of the study site) is 502 mm, with 366 mm falling as rain. Average annual winter precipitation (November - March) is 144 mm (Atmospheric Environment Service 1982*a*). The area averages 65 frost-free days per year (Atmospheric

Environment Service 1982*b*), with 1182 growing degree days above 5 °C annually (Atmospheric Environment Service 1982*c*).

Fifty hectares of this peatland were drained in 1984 using a backhoe to create a herringbone pattern of ditches with spacings of 25- and 40-m in the central, and western portions of the drained area, respectively. Ditches were 0.9 m deep and 1.4 m wide at the time of installation. Water tables before drainage varied from 0 to 38 cm below the ground surface. The year after drainage, mid-summer water table levels declined to 50-60 cm below the surface (Tóth and Gillard 1988).

2.1.1 Sampling

Peat was sampled from the area drained with 25-m ditch spacing and from an adjacent undrained (control) area. Sample plots were arranged in a complete-block design. Ten blocks extending from the drained area into the undrained area were established on the boundary of the drainage installation. The area was located along a shallow topographic gradient where the direction of groundwater flow was parallel to the perimeter ditch. This was done to ensure that minimal hydrologic influence of drainage had occurred on the adjacent undrained area (Hillman 1992). The drained portion of each block was located in different “ditch to ditch” drainage strips. A single sample plot was located within the drained and undrained portion of each block. Sample plots within the drained portion of each block were situated midway between drainage ditches in relatively flat areas, intermediate in elevation between hummock tops and hollow bottoms. Plots in the undrained portion of the blocks were located 80-90 m away from the main perimeter ditches in areas with similar bryophyte composition and micro-topography as in the drained area. The study design was based on the assumption that the peatland within the drained and undrained areas were similar before drainage. Unfortunately, without extensive pre-drainage data this assumption cannot be validated with certainty. However, reports of similar pre-drainage saturated hydraulic conductivities (Tóth and Gillard 1988) and growth of black spruce and tamarack (Yin 1993) between present-day drained and undrained areas of Saulteaux River support this assumption. Two frozen rectangular peat cores (7x7x50 cm) were extracted from each plot using a chainsaw during the winter of 1990/91. This method allows sampling without disturbance of peat pore

structure (Jones *et al.* 1993).

2.1.2 Physical/Chemical Properties

Several peat properties were measured for general descriptive purposes, and to characterize differences in peat decomposition between drainage conditions. Five peat cores from each drainage condition (every other block) were sub-sectioned into four 10-cm depth increments using the peat surface (i.e. top of live moss layer) as the datum (0-10, 10-20, 20-30, and 30-40 cm). Samples were thawed, mixed, and sub-divided for the following analyses. pH of the moist peat in 0.01M $CaCl_2$ solution was determined with a pH probe (Fisher model 119) after Day (1988a). Percent ash of peat was determined by ignition of an oven dry sample in a muffle furnace at 550 °C for 2-3 hours. Peat particle density (milled, oven dry samples, approx. 2 g) was determined at 21°C by displacement with 99% ETOH using 50 ml pycnometers as described by Blake and Hartge (1986). Differences in peat decomposition between drainage conditions were measured using percent rubbed fibre and R-index methods. Rubbed fibre content provides an accurate index of degree of peat decomposition (Walmsley 1977). Fibres which are decomposed, but maintain their original structure are mechanically broken down in the measurement process. Rubbed fiber content was determined using the laboratory method described by Day (1988b). Samples were dispersed in calgon solution for 24 h, mixed in a milkshake blender for 10 minutes, and washed with 2% HCl through a 0.15 mm ASTM standard sieve. Peat R-factor, which indicates the recalcitrant peat fraction, was determined by acid digestion using the following method described by Gunther (1988). Peat was digested in 72% sulfuric acid for 5 h then diluted with water to 24 % H_2SO_4 and left overnight. The mixture was diluted to 1.8 % H_2SO_4 and boiled with a backflow cooler for 5 h. The sediment was filtered, oven dried for 4 h at 105 °C, weighed, ashed in a muffle furnace at 350 °C for 2 h and re-weighed. Peat R-factor was expressed as the ash-free non-hydrolyzable peat fraction (%). As R-factor indicates the recalcitrant peat fraction, higher values indicate greater degree of decomposition (Gunther 1988).

2.1.3 Soil Water Retention

The second core from each plot was sub-divided with a hand saw while still frozen into four depth increments as above. Each increment was further sub-divided into 7x7x8.5 cm and 7x7x1.5 cm sections for water retention measurements at high (-5, -10, -25, -50, and -100 cm head) and low (-300, -1000, -3000, and -15000 cm head) water potentials, respectively. Water retention at water potentials above -100 cm head was measured in Tempe cells constructed of Plexiglas after Reginato and van Bavel (1962). Aluminum oxide powder was used as a tension medium. The 30-45 μm particle size fraction had suitable characteristics; high conductivity and appropriate bubbling pressure for desorption work at pneumatic pressures less than 125 cm head. Saturated hydraulic conductivity of the tension medium was 2.34 cm/h measured using the constant head method (Klute and Dirksen, 1986) at four applied hydraulic pressure heads ranging from 29 to 93 cm head. A constant head apparatus using hanging water columns was used to regulate pneumatic pressure in each cell for desorption work. Outflow from each cell was collected in sealed flasks to prevent evaporation. Cumulative outflow was measured by weighing flasks at increasing time intervals after application of each pressure increment. Equilibrium soil water content at each pressure was determined by weighing Tempe cells after outflow ceased for a 24 h period. Time to equilibrium varied from 2 days at -5 cm head for low bulk density samples to 9.5 days at -100 cm head for higher bulk density samples. After equilibrium was reached at -100 cm head, the sample was weighed and oven dried to determine soil water content and bulk density. The wet weight and volume (by displacement) of roots, if present, were determined separately from the peat after water retention measurements were complete. Soil water content and bulk density were expressed on a root-free, saturated volume basis. The expression of root-free water content was used to reduce variability in bulk density and water content due to the possible presence of large roots in individual samples. Cumulative outflow was used as a check for soil water contents determined by weighing cells. Water retention at lower water potentials (-300, -1000, -3000, and -15000 cm head) was measured using pressure plate apparatus (Soil Moisture Corp. #1500 and #1600). Shrinkage of samples during outflow measurement was determined by re-measuring sample volume after equilibrium was reached

at -100 head. Pore size distribution was estimated from water retention using the capillary rise equation (Hillel 1980).

2.1.4 Hydraulic Properties

Saturated and unsaturated hydraulic conductivities were measured from outflow of each sample using inverse parameter estimation procedures for multi-step outflow experiments (van Dam *et al.* 1990, 1993). This method was chosen as it is easily combined with measurement of soil water retention characteristics using the volumetric desorption apparatus adopted in this study. The procedure requires measurement of cumulative outflow as a function of time from an initially saturated soil core subjected to a series of pneumatic pressure step increments. Drainage as a result of the imposed water potential gradient is described by Richard's equation in its vertical one-dimensional form with z positive downward.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] \qquad [2\text{-}1]$$

The combined system of soil and porous plate has the following initial and boundary conditions:

$$h = h_o(z) \qquad t = 0 \qquad 0 \le z \le L \qquad [2\text{-}2a]$$

$$\frac{\partial h}{\partial z} = 1 \qquad t > 0 \qquad z = 0 \qquad [2\text{-}2b]$$

$$h = h_L - h_a \qquad t > 0 \qquad z = L \qquad [2\text{-}2c]$$

where z=0 is the top of the soil core, L is the combined height of the soil core and porous plate, h_L is the initial pressure head below the plate, and h_a is the applied pneumatic pressure. The initial condition [2-2a] specifies uniform head distribution throughout the core at the beginning of the experiment. The boundary condition [2-2b] specifies that no additional water is added to the top of the core. Boundary condition [2-2c] indicates the total pressure head gradient is established by application of pneumatic pressure increments (i.e. the suction head at the bottom of the porous plate is equivalent to the applied pneumatic pressure head). The technique involves fitting parametric models describing soil water retention and unsaturated hydraulic conductivity (Mualem 1976, van Genuchten 1980) to outflow from the controlled flow event.

The recently developed MULSTP model of van Dam *et al.* (1990, 1993) extends the ONE-STEP outflow model of Kool *et al.* (1985) to the multi-step outflow case generated during measurement of soil water retention. Inverse determination of soil hydraulic functions from multi-step outflow experiments are reviewed by van Dam *et al.* (1990, 1993, 1994), Marion *et al.* (1994), Eching *et al.* (1994), and Crescimanno and Iovino (1995). Multi-step outflow procedures avoid the high (potentially non-Darcian) initial fluxes associated with one-step outflow procedures by imposing small progressive pressure increments rather than one large pressure step. More uniform changes in water potential and conductivity within the sample are associated with smaller progressive pressure steps, thus outflow contains more information about the mean hydraulic properties of the sample (van Dam *et al.* 1990).

The model MULSTP uses a Galerkin finite element routine to solve Richard's equation [2-1] for unsaturated flow using the Mualem-van Genuchten soil hydraulic functions:

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) \qquad [2\text{-}3]$$

$$h(S_e) = [(S_e^{-1/(1-1/n)} - 1)^{1/n}] / \alpha \qquad [2\text{-}4]$$

$$K(S_e) = K_s S_e^{\lambda} [1 - (1 - S_e^{1/(1-1/n)})^{1-1/n}]^2 \qquad [2\text{-}5]$$

where S_e is the reduced volumetric soil water content; θ, θ_r, and θ_s are the actual, residual, and saturated volumetric water contents; h (L) is the hydraulic head; K and K_s (L T^{-1}) are the unsaturated and saturated hydraulic conductivities; α (L^{-1}), n, and λ are empirical parameters. The parameters α and n describe the shape of the water retention function [2-4], where α indicates the inverse of the pressure head at the air entry value (i.e. hydraulic head at which water will begin to flow), and n describes the mean slope of the desorption curve, or the range of the pore size distribution. The parameters K_s and λ describe the shape of the conductivity function [2-5], where K_s is a scaling factor that shifts the $\partial K/\partial h$ function up or down, and λ indicates the mean slope of the $\partial K/\partial h$ relationship (van Dam *et al.* 1990). Saturated and residual water content determine the range of θ. Cumulative outflow $Q_c(t_i, b)$ at time t_i is calculated for the set of parameters contained in vector b (i.e. α, n, K_s, and λ). The function $O(b)$ describes the difference between observed outflow $Q_o(t_i)$ and predicted outflow $Q_c(t_i, b)$ at time t_i [2-6].

$$O(b) = \sum_{i=1}^{N} [Q_o(t_i) - Q_c(t_i, b)]^2 \qquad [2\text{-}6]$$

$$O(b) = \sum_{i=1}^{N1} \{w_i [Q_o(t_i) - Q_c(t_i, b)]\}^2 + \sum_{i=1}^{N2} \{W_1 v_i [\theta_o(h_i) - \theta_c(b, h_i)]\}^2 \qquad [2\text{-}7]$$

The water retention function $\theta(h)$ can be included in $O(b)$ in a combined objective function that optimizes both outflow and water retention [2-7], where w_i and v_i are weighting factors, N1 and N2 are the number of observations for outflow and water retention data, and W_1 is a normalization factor for water retention data. The weighting factors can be used to account for differences in accuracy of measurement, and the normalization factor adjusts the right hand portion of equation [2-7] for differences in scale between outflow and retention data. A non-linear parameter estimation routine is used to minimize the function $O(b)$ by varying parameters in vector b. Final parameter values are those that minimize $O(b)$. Initial parameter estimates must be reasonably close to final optimized values as the solution is sensitive to local minima.

Outflow from four pneumatic pressure increments (10, 25, 50, and 100 cm head) were used in the optimization procedure. The first pressure step (5 cm head) was omitted as non-uniform flow can occur in experiments starting from saturation (van Dam *et al.* 1994, Hopmans *et al.* 1992) violating the uniform flow assumption of the model. Saturated water content θ_s was determined by weighing Tempe cells after saturation for 24 h. Residual water content θ_r was defined by Mualem (1976) as θ where $K \to 0$ or $\partial h/\partial\theta \to \infty$, a condition strictly met at $\theta=0$. I fixed $\theta_r = 0$ after Marion *et al.* (1994), and van Dam *et al.* (1994). Initial values for α and n were obtained by fitting equation [2-4] to the measured water retention (θ at h=-5 to -15000 cm) of each sample using a non-linear parameter estimation routine. Saturated hydraulic conductivity can either be independently measured and included as an input parameter (Marion *et al.* 1994) or optimized as a fitting parameter (van Dam *et al.* 1994, Eching *et al.* 1994). As no independent measurement of saturated hydraulic conductivity was made, K_s was included as a fitting parameter in the optimization. Initial values of K_s were estimated using relationships between bulk density and K_s reported for various peat types by Boelter (1969) and Päivänen (1973). K_s was calculated for each sample as a function of bulk density using linear relationships reported by both authors and averaged.

Though Eching *et al.* (1994) concluded that optimized K_s has no physical meaning because it occurs outside of the optimization range, Marion *et al.* (1994) suggests better estimates of K_s are possible if optimization includes outflow in the wetter range of $\theta(h)$. The first pressure step in this study (10 cm head) was considerably lower than that used by Eching *et al.* (1994), Marion *et al.* (1994), or van Dam *et al.* (1994). I interpreted optimized K_s cautiously in light of differences observed in other physical and hydrologic characteristics between drained and undrained peat. Lambda was included as a fitting parameter in the optimization as suggested by van Dam *et al.* (1994). In preliminary analysis on a subset of samples (n=4 for each depth and drainage condition) using different initial parameter estimates, optimized values for λ varied from -3.8 to -4.99. An initial value of -4.25 for λ was used for all samples with the full data set. Optimization was done using initial estimates described above, and with two other sets of initial estimates to confirm the location of global minima.

Optimizations using three different approaches were performed: 1) optimization of α, n, K_s, and λ from outflow alone (objective function [2-6]); 2) optimization of K_s and λ as in 1), but using fixed values of α and n obtained from fitting retention data to equation [2-4], and 3) optimization of α, n, K_s, and λ using both outflow and water retention data (objective function [2-7]). Weighting factors (w_1, v_1) were set to 1 giving equal weight to outflow and water retention data in the third optimization approach. Results from these three approaches are presented in Appendix 1. Though final values of hydrologic parameters varied among these approaches, differences between drainage conditions and depths were generally similar. However, predicted outflow and water retention differed between approaches 1) and 2). The first approach predicted transient outflow well (r^2=0.977), but predicted water retention poorly (r^2=0.866). Conversely, the second approach provided a good fit to observed water retention (r^2=0.982) but predicted outflow poorly (r^2=0.903). The third approach predicted outflow accurately (r^2=0.968) and provided a better prediction of water retention (r^2=0.955) than in approach 1). van Dam *et al.* (1992, 1994) concluded that supplementary equilibrium $\theta(h)$ data are needed in outflow experiments to avoid problems with non-unique parameter estimates

(i.e. a similar flow response can be generated using different parameter values) reported by others. Results from the third approach are reported here.

2.1.5 Statistical analysis

Differences in peat chemical/physical properties, bulk density, and soil hydrologic parameters among drainage conditions and depths were tested using ANOVA procedures for block designs. Differences in soil water retention and unsaturated hydraulic conductivity $K(h)$ among drainage conditions and depths were tested using repeated measures MANOVA. Hydraulic conductivity and water potential data were log transformed to satisfy assumptions of analysis of variance. Fixed factors were tested against their interaction with the random factor "block" in both analysis of variance procedures (Milliken and Johnson 1984). Tests for coincident regressions was performed according to Zar (1974).

2.2 RESULTS

Variation in degree of decomposition as indicated by % rubbed fibre and R-factor was observed among depth increments and drainage conditions, while variation was weak or absent in other peat properties (Table 2-1). Particle density, pH, and % ash were least variable by depth and drainage condition. Variation in pH by depth was evident ($p=0.049$) due to several low values observed in the surface 0-10 cm depth in the undrained area. Though interaction effects between depth and drainage were observed for pH ($p=0.059$) and % ash ($p=0.045$), no consistent trends were evident. Mean particle density was 1.494 and 1.496 g/cm^3 in the drained and undrained areas, respectively, and was the least variable property measured. Greater variation was observed in degree of peat decomposition. Mean rubbed fibre content (0-40 cm depth) was 50.83 % and R factor was 49.64 % in undrained areas compared to 38.94 % ($p=0.028$) and 56.85 % ($p=0.093$) for both decomposition indices in drained areas. These results indicate a greater degree of peat decomposition existed in drained compared to undrained areas. Rubbed fibre content decreased ($p<0.001$) and R factor increased ($p=0.007$) with depth in both drainage conditions. No interaction between drainage and depth effects were evident for either measure. The greatest differences in peat decomposition between drained and undrained areas (both measures) were in the surface 0-20 cm.

Differences in peat bulk density, water retention, and pore size distribution were observed between drained and undrained areas. Roots were generally absent from most of the samples (averaged 1.7% of total sample volume), thus expression of water content and bulk density on a root-free basis had little influence on the reported values. Mean bulk density (0-40 cm depth) of drained peat was 63 % higher ($p<0.001$) than peat from undrained areas (0.129 Mg/m^3 and 0.079 Mg/m^3, respectively). Bulk density increased with depth ($p<0.001$) in both drainage conditions (Figure 2-1b). Bulk density of drained peat was over three times greater than that of undrained peat within 10 cm of the surface, and over two times greater at 10-20 cm depth. Differences between drained and undrained peat decreased to 20 % at 30-40 cm depth.

Mean water retention of peat from the drained area was greater than in peat from the undrained area ($p<0.001$) at all water potentials below saturation (Figure 2-1a). Water retention increased with depth in both drainage conditions ($p<0.001$). Mean water retention from -5 to -15000 cm head for undrained peat was 8, 21, 37, and 46 % by volume for the four 10-cm depth increments respectively, while drained samples retained 27, 47, 54 and 57 % water over the same depths. Differences in water retention between drained and undrained peat roughly paralleled differences observed in bulk density. Water content of drained peat was approximately three times greater than undrained peat from 0-10 cm depth at all water potentials other than saturation. As with bulk density, differences in water retention between drained and undrained peat decreased with depth ($p=0.077$) from two fold differences evident at 10-20 cm depth, to a 20 % difference at 30-40 cm depth. The shape of the water retention functions ($\partial\theta/\partial h$) also varied among depths and drainage conditions. Though the slope of the water retention function between -5 and -15000 cm head increased with depth in both drainage conditions ($p<0.001$), this gradient was considerably steeper in samples from the drained area than from the undrained area at all four depths ($p<0.001$). An interaction effect of depth and drainage condition on the $\partial\theta/\partial h$ gradient was not observed ($p=0.338$).

Variation in water retention can be related to differences in pore size distribution among different depths and drainage conditions (Table 2-2). Both drained and undrained peat contained a high proportion of large pores (>600 μm dia.) in surface layers (0-10 cm depth) with low bulk density. A shift from

large to small pore sizes was associated with higher bulk density peat found at greater depths in both areas, however the concurrent increase in volume of smaller pores was not uniform across pore size classes. A bi-modal distribution of pore size classes was associated with higher bulk density at depth in both drained and undrained peat. The greatest relative increase in pore volume corresponding to loss of large pores (>600 μm dia.) was in the 3-30 μm dia. pore size class. Pores in this diameter range drain between -100 and -300 cm head. Peat from the drained area contained a lower proportion of large pores and greater proportion of small pores at all four depths. The shift in pore sizes from >600 to 3-30 μm dia. at greater depths was more strongly evident, and occurred shallower in drained peat than in undrained peat.

Some sample shrinkage occurred between saturation and -100 cm head. Mean sample volume was reduced by 4.5% in drained peat, and 6.5% in undrained peat during the outflow experiment (Appendix 2). This resulted in an underestimation of water content by 2.58% θv and 2.42% θv for drained and undrained peat, respectively. However, the magnitude of these errors were less than the variation among replicate samples for drainage conditions and depths observed in this study. In addition, no discontinuity in the shape of the water retention curves between -5 to -100 cm head, and -300 to -15000 cm head was evident. This supports the assumption of negligible loss of soil-plate contact during the outflow experiment. Based on the criteria for multi-step outflow experiments described by Crescimanno and Iovino (1995), errors in the estimation of hydrologic parameters caused by shrinkage, and loss of contact between the soil and pressure plate were considered negligible (Appendix 2).

Inverse determination of hydrologic parameters from outflow data indicated differences in peat hydrologic characteristics between drainage conditions (Table 2-3). Parameters describing the shape of water retention functions varied among depths and drainage conditions. Alpha decreased with depth in both drainage conditions ($p<0.001$), and was lower in drained peat than in undrained peat ($\alpha=16.06$ cm^{-1}, and 108.54 cm^{-1} respectively, $p=0.001$) indicating drained peat had slightly lower air entry matric potentials. An interaction effect of depth and drainage was evident for α which decreased more rapidly with depth in undrained peat compared to drained peat ($p=0.035$). Conversely, n increased with depth ($p=0.014$) and was greater in

drained peat (mean n=1.32) than in undrained peat (mean n=1.26) indicating the mean slope of the water retention curves was slightly steeper in peat from the drained area (p=0.066). A depth by drainage interaction was also observed for n (p=0.027) due to several high values observed in the 0-10 cm depth increment in undrained peat.

Mean predicted water retention based on α and n was generally similar to observed water retention (Figure 2-1a). Predicted water contents at saturation and -15000 cm head closely corresponded to observed water contents for all depths and drainage conditions. The best prediction of water contents at intermediate water potentials (-5 to -3000 cm head) was observed in lower bulk density samples (0-20 cm depth for drained peat, 0-30 cm depth for undrained peat). The model overestimated water contents at intermediate water potentials for higher bulk density samples from greater depths in both drainage conditions. The greatest discrepancy between predicted and observed water retention was at 20-30 cm depth in drained peat (overestimated mean $\theta(h)$ by 5.9 %) and at 30-40 cm depth in undrained peat (overestimated mean $\theta(h)$ by 4.8 %).

Parameters describing the shape of the $K(h)$ relationships also differed among depths and drainage conditions (Table 2-3). Mean (0-40 cm depth) optimized saturated hydraulic conductivity (K_s) was 1.69 cm/h in drained peat compared to 14.46 cm/h in undrained peat (p=0.002), and decreased with depth in both drainage conditions (p<0.001). No interaction between depth and drainage condition was evident (p=0.573). Saturated hydraulic conductivity decreased as bulk density increased (p<0.001) in both drainage conditions (Figure 2-2). Overall, bulk density explained 73% of the variation in log(K_s). The relationship between log(K_s) and bulk density did not differ between drained and undrained peat (p=0.918). Mean λ was -4.835 overall, and did not vary among depths (p=0.653) or drainage conditions (p=0.564). No interaction effects between depth and drainage were evident for λ (p=0.091).

Variation in these hydrologic parameters was associated with differences in unsaturated hydraulic conductivity among depths and drainage conditions. Unsaturated hydraulic conductivity decreased as peat water potential was lowered (p=0.001) in both drainage conditions (Table 2-4). Mean $K(h)$ (0-40 cm depth) was greater in drained peat than in undrained peat (0.0144 cm/h and

0.0041 cm/h, respectively, $p=0.036$), but was similar among depths for both drainage conditions ($p=0.812$). Interactions between drainage and depth ($p=0.120$), and drainage and water potential ($p=0.074$) were not evident for unsaturated hydraulic conductivity. Differences in water transport characteristics were more apparent in unsaturated hydraulic conductivity as a function of water content $K(\theta)$. Mean $K(\theta)$ of drained peat was greater than undrained peat at all 4 depths over the range of moisture contents observed for peat from each drainage conditions (Figure 2-3). The slope of the $K(\theta)$ relationship in drained peat was less than that of undrained peat at all four depths. The steepest $K(\theta)$ gradients (i.e. large reduction in K over a narrow range of θ) were evident in the 0-10 and 10-20 cm layers of peat from the undrained area. Smaller reductions in K over a wider range of θ were observed in undrained peat at 20-30 and 30-40 cm depths. A similar reduction in the slope of this relationship with depth was not evident in drained peat.

2.3 DISCUSSION

Differences in peat properties between drained and undrained areas confirm subsidence occurred during the six years after drainage of the Saulteaux River peatland. The differences between drainage conditions observed in this study probably underestimated the effects of subsidence as peat was sampled midway between ditches where subsidence would have been least (Lukkala 1949, Rothwell *et al.* 1996).

Differences in bulk density between drainage conditions were similar in magnitude to those reported by others for much older drained peatlands. Though greater decomposition of cellulose and *Sphagnum* was observed after drainage, Lieffers (1988) reported no significant increase in bulk density to 30 cm depth in the 40-m ditch spacing of Saulteaux River two years after drainage, while Rothwell *et al.* (1996) reported a relative increase in bulk density of 46 % for the same depths 3-4 years after drainage of three other Alberta peatlands. In the present study, mean bulk density six years after drainage was 90 % greater than that of undrained areas from 0-30 cm depth. Old forest drainage areas do not exist in Alberta, however in Finland, Laine *et al.* (1994), and Laiho and Laine (1992) reported differences in bulk density between undrained and peatlands drained 60 years earlier of similar magnitude to those observed in the present study. These findings support

Lukkala's (1949) suggestion that most subsidence occurs within 10 years of drainage. Such findings also support the conclusions of Laine *et al.* (1994) that considerable variation in post-drainage subsidence can be expected among different forested peatlands types and climatic regions.

Increased peat bulk density due to post-drainage subsidence altered the pore characteristics of surface peat at Saulteaux River. Subsidence was associated with loss of pores > 600 μm in diameter with a concurrent increase in smaller pores (particularly in the 3-30 μm diameter range). Though this observation supports the conclusions of Burghardt and Ilnicki (1978) and Egglesman (1975) who suggested subsidence of surface layers is associated with collapse of readily drainable macro-pores, comparison of results with studies conducted on repeatedly drained and cultivated agricultural peatlands (McLay *et al.* 1992, Burghardt and Ilnicki 1978) is difficult due to large differences in initial soil characteristics.

Several earlier studies used easily measured soil properties to estimate hydraulic functions of organic soils (Bloemen 1983, Brandyk et al. 1985, da Silva *et al.* 1993). However, the MULSTP model of van Dam *et al.* (1993) offers advantages over these earlier methods in that both water retention characteristics and transient unsaturated flow data are used in the estimation procedure. In MULSTP, iterative verification of hydraulic functions is performed for each observation by comparing predicted unsaturated flow using estimated hydrologic parameters to observed flow. Though this verification is not independent from the data on which the model is fit, the procedure ensures that estimated hydraulic parameters are those that best describe the unique flow characteristics of each sample. Results of analysis in Appendix 2 suggest that the multi-step outflow method can be applied to some organic soils. Errors in estimation of hydrologic parameters caused by preferential flow, and soil shrinkage during outflow (Crescimanno and Iovino 1995) were probably negligible for the soils considered in this study. The model provided good prediction of both water retention (r^2=0.96) and transient outflow (r^2=0.97) (Appendix 1). As saturated and unsaturated hydraulic conductivity were not measured using other techniques, independent verifications of these data were not possible. However, the range of values, and differences in conductivities observed among depths and drainage conditions agree favorably with direct

measurements reported for various peat types by Boelter (1965, 1969), Päivänen (1973), von Bartels and Kuntze (1973), and Renger *et al.* (1976).

Despite uncertainty regarding absolute values of optimized saturated hydraulic conductivity, the relationship between K_s and bulk density (Figure 2-2) is generally consistent with that reported by Boelter (1969) and Päivänen (1973). The decrease in optimized K_s as bulk density increased was somewhat greater than reported by Boelter (1969) and Päivänen (1973), however results from this study are within the range of variation observed by both authors. Though the relationship observed in this study (r^2=0.73) was less variable than that reported by Boelter (1969) (r^2=0.54), and Päivänen (1973) (r^2=0.17 to 0.51), initial estimates of K_s were based on linear relationships reported by these authors. The extent to which final optimized values of K_s were influenced by the initial linear estimates is not known. Reduction of K_s due to post-drainage subsidence was consistent with the magnitude of increased bulk density and shift in pore size distribution. This finding supports the observations of Burghardt and Ilnicki (1978) who report increased residence time of percolating water after subsidence of repeatedly drained agricultural peatlands in Germany. Though decreases in K_s could also be expected to alter the efficiency of existing ditch spacings (Boelter 1972), large changes in sub-surface flow to ditches appear unlikely as subsidence effects on saturated hydraulic conductivity diminished with depth. The observed reduction in saturated hydraulic conductivity at 40 cm depth is probably not sufficient to cause a large reduction in saturated flow to drainage ditches.

Changes in pore size distribution due to subsidence were also associated with increased soil water retention below saturation. Differences in water retention and transport characteristics between drained and undrained peat at Saulteaux River were similar to those between undecomposed and highly decomposed peat reported by Päivänen (1973) and Boelter (1964, 1965, 1969). However, changes to these characteristics resulting from post-drainage subsidence have not, to my knowledge, been previously reported in the literature. Loss of large pores (which drain freely under gravity) due to subsidence was associated with reduction of soil water content between saturation and -5 cm head in favor of increased water retention at potentials below -5 cm head. In terms of water storage, detention storage (i.e. easily drainable porosity) was decreased in favor of increased retention storage (plant

available and unavailable soil water). Though this finding supports the conclusions of Rothwell *et al.* (1996) who observed greater peat water contents after drainage and subsidence of three forested Alberta peatlands, the availability of increased soil water observed in their study was not defined. 'Readily available' soil water for tree growth was defined by Päivänen (1973) as water retained between pF 1.5 (-32 cm head) and pF 3.0 (-1000 cm head), and 'decreasingly available' water as that held between pF 3.0 and 4.2 (-15000 cm head). At Saulteaux River, approximately 3 fold increases in both 'readily available' and 'decreasingly available' soil water were associated with post-drainage subsidence of peat within the surface 40 cm (Figure 2-4a). However, unsaturated hydraulic conductivity (i.e. the ease of soil water withdrawal by tree roots) and its rate of change during water removal are of equal importance to the amount of water held within these water potential ranges. Mean unsaturated hydraulic conductivity of drained peat was roughly 5 times greater than undrained peat over the 'readily available' water range, and nearly 15 times greater over the 'decreasingly available' water range (Figure 2-4b). Analysis of variance indicated no differences existed in the slope of the $K(h)$ relationship between drainage conditions, thus post-drainage subsidence increased both the amount of plant available soil water and the ease with which that water could be taken up by roots.

2.4 CONCLUSION

Though some effects of subsidence after drainage of forested peatlands has been reported in northern Europe and Canada, to my knowledge, the effects of subsidence on surface peat hydrologic characteristics have not been previously reported. Greater bulk density and concurrent shifts in peat pore size distribution were associated with subsidence in the area of Saulteaux River drained with 25-m ditch spacing. This resulted in increased water retention and altered soil water transport characteristics within the surface 40 cm. Increased post-drainage water retention was approximately proportional to observed increases in peat bulk density. The amount of 'readily available' soil water for tree growth was increased, as was the unsaturated hydraulic conductivity over the same soil water potential range. In terms of water relations, post-drainage subsidence probably improved peat soils for tree growth at Saulteaux River.

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Table 2-1 Mean properties of peat from drained and undrained areas of Saulteaux River for four depth increments. Values in brackets indicate 1 standard error (n=5).

	Depth Increment			
	0-10 cm	10-20 cm	20-30 cm	30-40 cm
pH ($CaCl_2$)				
Drained	5.15 (0.131)	5.15 (0.083)	5.05 (0.072)	4.96 (0.032)
Undrained	4.24 (0.489)	5.17 (0.447)	5.25 (0.144)	5.19 (0.123)
% Ash				
Drained	7.36 (0.965)	6.64 (0.424)	5.62 (0.201)	5.71 (0.379)
Undrained	5.31 (0.733)	7.49 (1.294)	8.21 (0.962)	7.14 (0.725)
Particle Density				
Drained	1.496 (0.004)	1.497 (0.008)	1.496 (0.015)	1.496 (0.006)
Undrained	1.470 (0.026)	1.505 (0.018)	1.513 (0.003)	1.496 (0.007)
% Rubbed Fibre				
Drained	43.87 (2.69)	38.01 (3.802)	36.29 (1.498)	37.60 (1.321)
Undrained	69.75 (5.64)	57.87 (9.25)	39.81 (1.092)	35.90 (4.660)
% R Factor[1]				
Drained	53.91 (1.978)	54.53 (3.148)	56.17 (2.334)	62.79 (1.671)
Undrained	42.30 (4.461)	47.69 (4.798)	54.55 (1.453)	54.02 (1.668

[1] Recalcitrant peat fraction (higher values indicate greater decomposition)

Table 2-2 Mean fractional pore volume for different pore size classes for drained and undrained peat from Saulteaux River for four depth increments. Values in brackets indicate 1 standard error (n=10).

Pore Diameter Size Class (μm)					
>600	600-120	120-30	30-3.0	3.0-0.2	<0.2
0-10 cm Depth					
Drained					
0.496 (0.058)	0.091 (0.030)	0.087 (0.011)	0.109 (0.021)	0.063 (0.010)	0.154 (0.019)
Undrained					
0.841 (0.014)	0.032 (0.006)	0.035 (0.004)	0.023 (0.006)	0.025 (0.004)	0.046 (0.011)
10-20 cm Depth					
Drained					
0.211 (0.027)	0.077 (0.005)	0.167 (0.012)	0.215 (0.016)	0.103 (0.008)	0.227 (0.020)
Undrained					
0.618 (0.060)	0.065 (0.015)	0.089 (0.016)	0.086 (0.020)	0.047 (0.008)	0.095 (0.017)
20-30 cm Depth					
Drained					
0.148 (0.020)	0.050 (0.006)	0.176 (0.008)	0.253 (0.017)	0.142 (0.008)	0.231 (0.013)
Undrained					
0.320 (0.045)	0.082 (0.008)	0.156 (0.011)	0.185 (0.019)	0.101 (0.009)	0.157 (0.019)
30-40 cm Depth					
Drained					
0.096 (0.015)	0.030 (0.008)	0.150 (0.006)	0.295 (0.018)	0.189 (0.027)	0.241 (0.021)
Undrained					
0.239 (0.034)	0.067 (0.010)	0.179 (0.011)	0.210 (0.014)	0.157 (0.025)	0.148 (0.024)

Table 2-3 Mean optimized Mualem-van Genuchten hydrologic parameters of drained and undrained peat from Saulteaux River for four depth increments. Values in brackets indicate 1 standard error (n=10).

	Depth Increment			
	0-10 cm	10-20 cm	20-30 cm	30-40 cm
α (cm^{-1})				
Drained	58.68 (30.45)	1.347 (0.69)	0.45 (0.44)	0.03 (0.01)
Undrained	298.86 (59.21)	127.99 (59.92)	4.06 (1.88)	3.17 (2.70)
n				
Drained	1.212 (0.026)	1.282 (0.041)	1.380 (0.034)	1.480 (0.091)
Undrained	1.329 (0.016)	1.224 (0.011)	1.225 (0.027)	1.288 (0.062)
K_s (cm/h)				
Drained	158.4 (77.9)	7.40 (3.47)	5.00 (4.60)	0.2 (0.1)
Undrained	551.4 (137.5)	340.71 (109.4)	15.33 (9.6)	37.2 (35.5)
λ				
Drained	-4.99 (0.01)	-4.49 (0.40)	-4.99 (0.01)	-4.99 (0.01)
Undrained	-4.50 (0.26)	-4.98 (0.01)	-4.99 (0.01)	-4.79 (0.19)

Table 2-4 Mean water content (θ) and unsaturated hydraulic conductivity (K) of drained and undrained peat from Saulteaux River at different water potentials (h) for four depth increments. Values in brackets indicate 1 standard error (n=10).

	Drained				Undrained			
h (cm)	θ (v/v)		K (cm/h x 10^{-4})		θ (v/v)		K (cm/h x 10^{-4})	
0-10 cm depth								
0	0.945	(0.010)	---	---	0.987	(0.006)	---	---
5	0.466	(0.059)	540.702	(395.205)	0.148	(0.015)	144.955	(42.544)
10	0.414	(0.051)	169.583	(109.528)	0.135	(0.013)	115.434	(38.703)
25	0.370	(0.046)	109.984	(77.715)	0.115	(0.014)	54.145	(14.105)
50	0.325	(0.041)	74.910	(55.895)	0.094	(0.012)	26.620	(7.147)
100	0.281	(0.035)	55.133	(42.713)	0.075	(0.010)	13.908	(4.480)
300	0.224	(0.030)	23.198	(18.016)	0.068	(0.004)	11.758	(7.107)
1000	0.162	(0.025)	15.990	(12.571)	0.047	(0.005)	5.048	(2.488)
3000	0.128	(0.019)	12.860	(10.205)	0.035	(0.004)	1.167	(0.427)
15000	0.101	(0.018)	3.955	(3.112)	0.024	(0.002)	0.514	(0.205)
10-20 cm depth								
0	0.942	(0.013)	---	---	0.964	(0.012)	---	---
5	0.730	(0.024)	237.931	(70.141)	0.369	(0.064)	177.318	(131.562)
10	0.705	(0.026)	203.017	(65.241)	0.344	(0.058)	116.277	(88.483)
25	0.654	(0.026)	142.994	(50.826)	0.299	(0.052)	41.127	(29.885)
50	0.585	(0.023)	90.470	(33.368)	0.249	(0.045)	13.358	(9.881)
100	0.487	(0.019)	52.350	(21.678)	0.204	(0.037)	4.652	(3.627)
300	0.382	(0.025)	33.677	(18.035)	0.167	(0.015)	2.692	(1.986)
1000	0.272	(0.017)	16.846	(10.183)	0.120	(0.016)	0.261	(0.121)
3000	0.210	(0.014)	10.527	(6.542)	0.095	(0.015)	0.060	(0.027)
15000	0.169	(0.016)	9.389	(6.039)	0.068	(0.011)	0.014	(0.009)
20-30 cm depth								
0	0.956	(0.010)	---	---	0.940	(0.016)	---	---
5	0.808	(0.019)	405.545	(119.406)	0.620	(0.046)	122.695	(72.652)
10	0.790	(0.021)	362.647	(108.257)	0.590	(0.044)	100.429	(63.631)
25	0.758	(0.021)	293.555	(84.008)	0.538	(0.044)	70.870	(49.230)
50	0.685	(0.022)	204.200	(58.071)	0.463	(0.039)	42.945	(31.933)
100	0.582	(0.019)	131.692	(39.894)	0.382	(0.033)	25.190	(19.529)
300	0.466	(0.009)	85.152	(30.358)	0.278	(0.028)	15.392	(12.210)
1000	0.329	(0.009)	49.121	(21.120)	0.197	(0.018)	7.516	(5.994)
3000	0.253	(0.010)	33.278	(17.359)	0.152	(0.018)	4.584	(3.655)
15000	0.187	(0.008)	24.896	(16.035)	0.097	(0.010)	2.006	(1.603)
30-40 cm depth								
0	0.930	(0.006)	---	---	0.976	(0.016)	---	---
5	0.826	(0.018)	365.365	(156.380)	0.736	(0.035)	107.325	(41.319)
10	0.818	(0.022)	355.596	(151.491)	0.716	(0.034)	87.435	(35.269)
25	0.786	(0.027)	301.099	(125.654)	0.662	(0.034)	56.401	(28.111)
50	0.734	(0.034)	252.351	(106.509)	0.588	(0.035)	37.879	(22.249)
100	0.639	(0.029)	185.575	(78.966)	0.494	(0.030)	23.422	(14.408)
300	0.502	(0.023)	128.649	(59.303)	0.394	(0.033)	13.707	(7.769)
1000	0.359	(0.024)	103.908	(52.822)	0.269	(0.027)	6.584	(3.717)
3000	0.286	(0.026)	98.613	(53.670)	0.209	(0.028)	4.391	(2.375)
15000	0.151	0.029)	90.993	(54.290)	0.104	(0.012)	1.100	(0.875)

Figure 2-1 Observed and predicted peat water content as a function of water potential (a), and bulk density (b) for drained and undrained peat from Saulteaux River for four depth increments. Error bars indicate one standard error (n=10). Values for predicted water retention are offset for clarity.

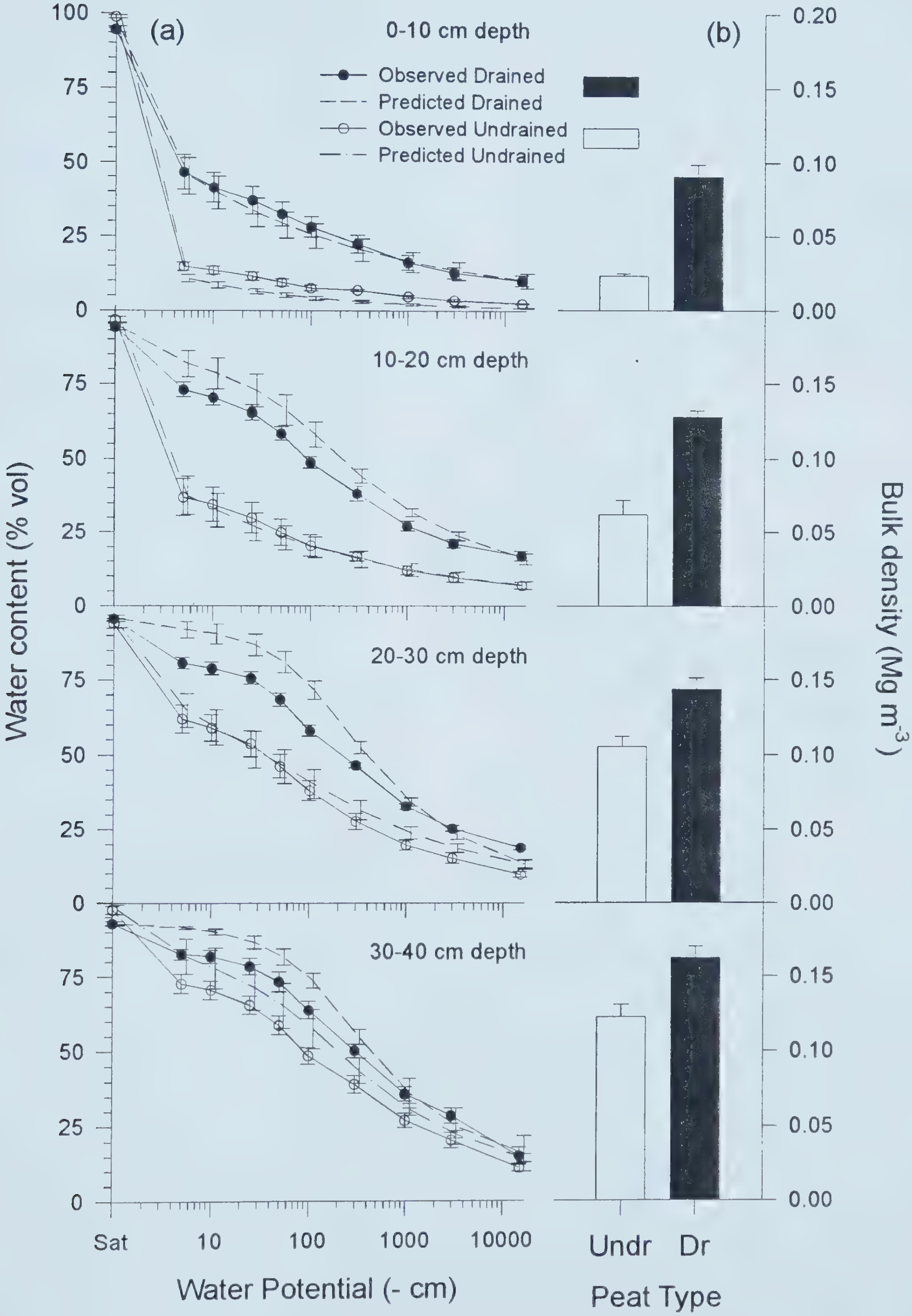


Figure 2-2 The relationship between saturated hydraulic conductivity and bulk density for drained and undrained peat from Saulteaux River for four depths. Broken lines indicate mean relationships observed for different peat types by Päivänen (1973) and Boelter (1969). Solid line and symbols indicate peat from the present study.

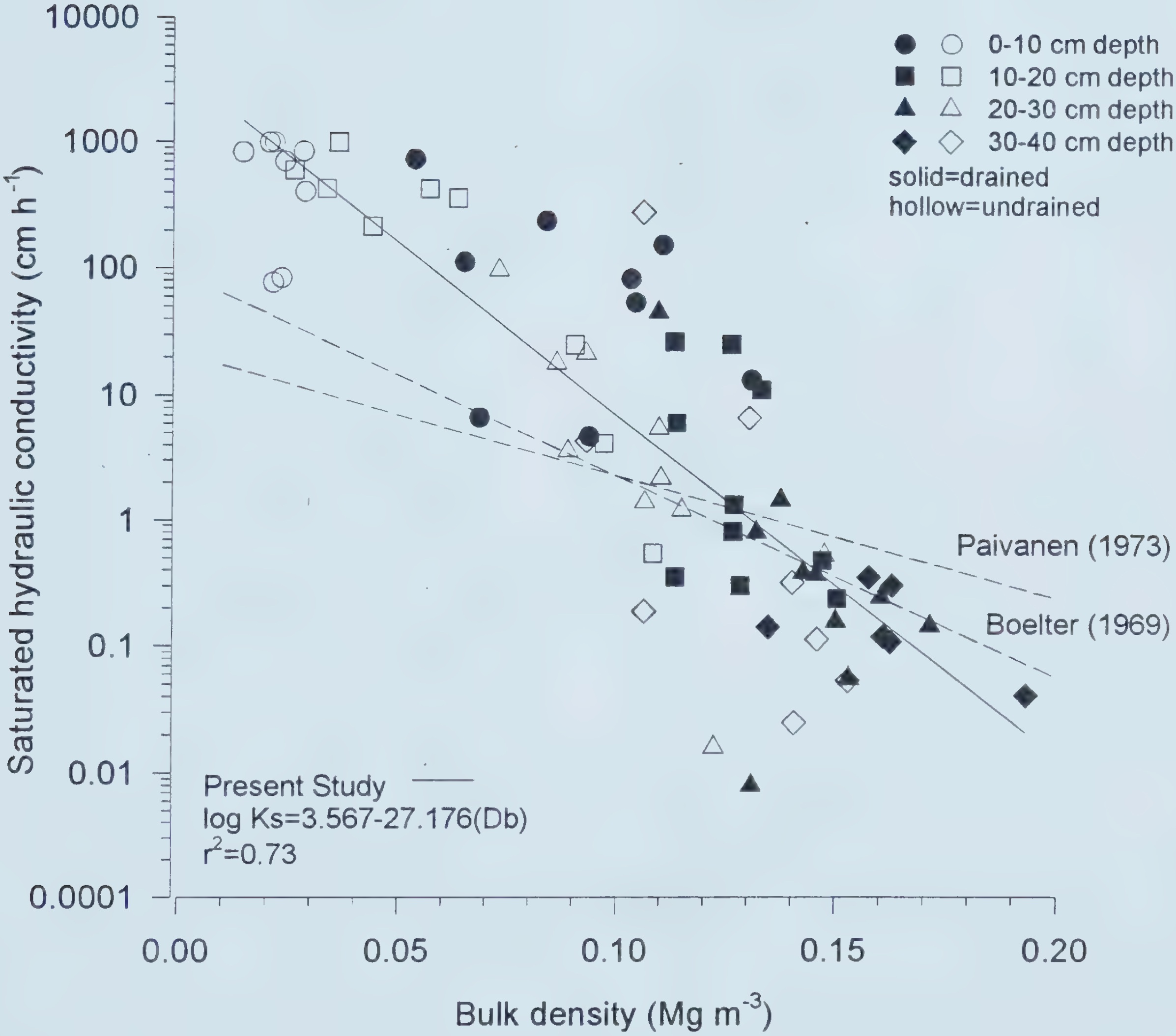


Figure 2-3 Unsaturated hydraulic conductivity K(θ) as a function of water content of drained and undrained peat from Saulteaux River for four depth increments. Values indicate means at water potentials from -5 to -15000 cm. Error bars indicate one standard error (n=10).

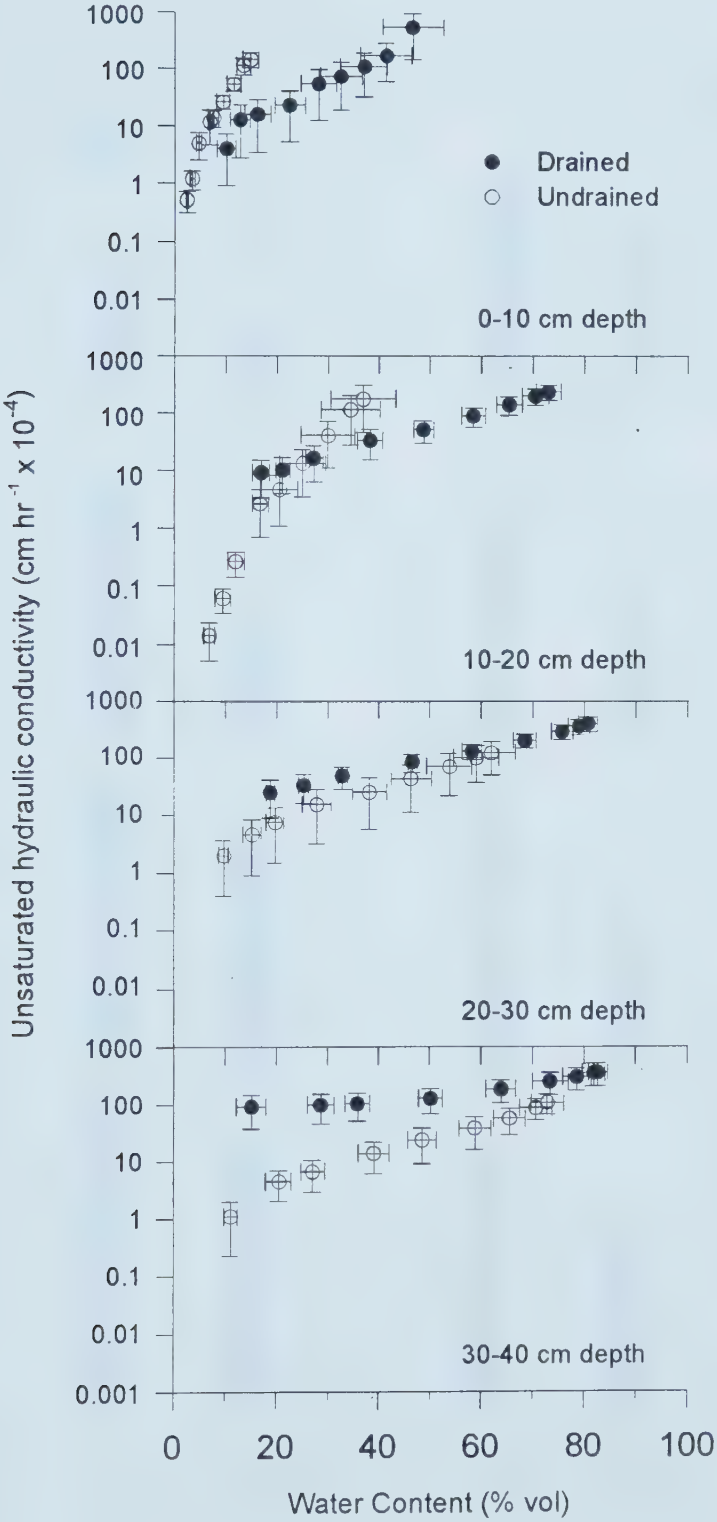
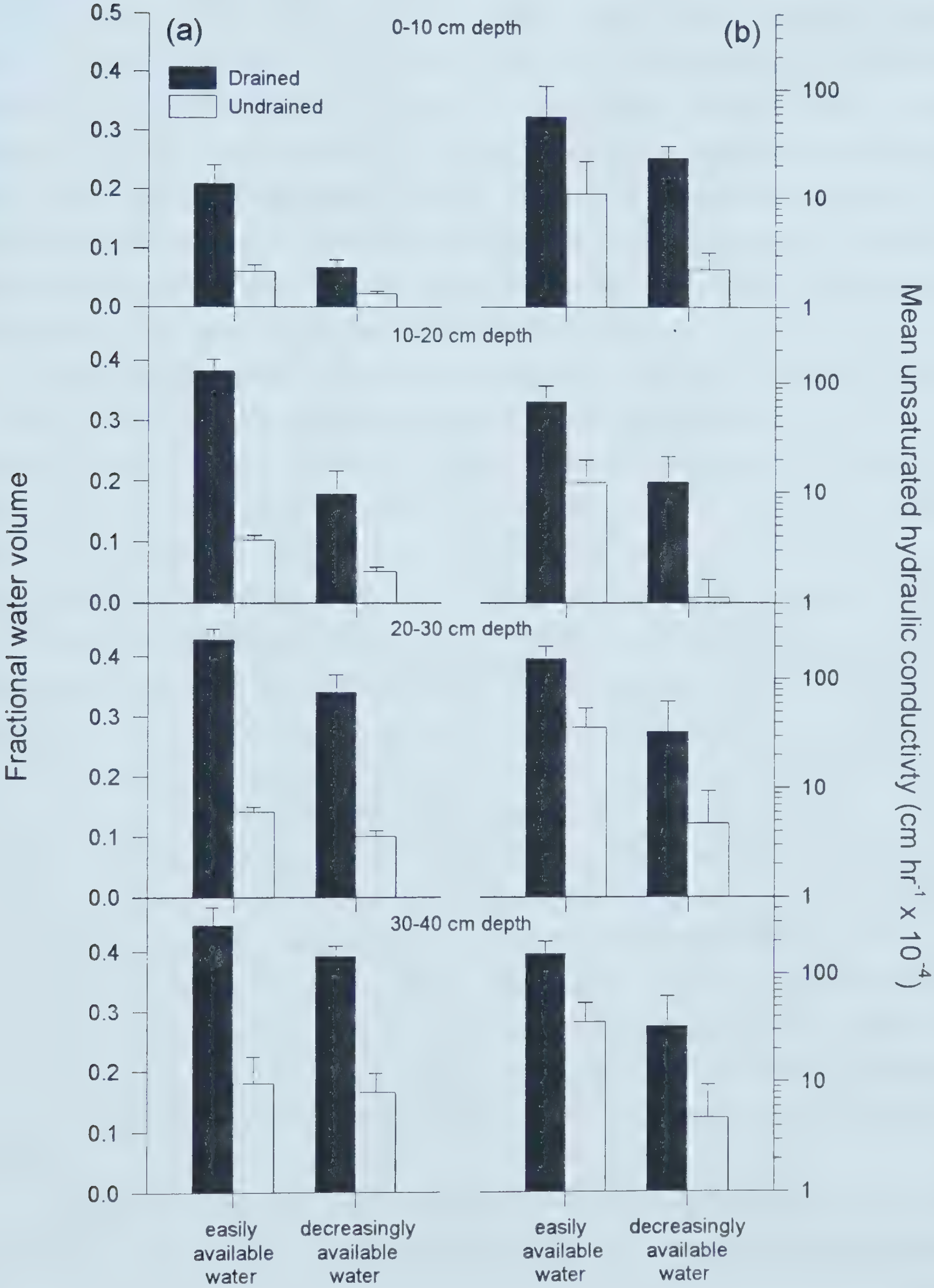


Figure 2-4 (a) Volume of soil water in easily available (-25 to -1000 cm head) and decreasingly available (-1000 to -15000) water potential ranges, and (b) mean unsaturated hydraulic conductivity over the same ranges in drained and undrained peat from Saulteaux River for four depth increments. Error bars indicate 1 standard error (n=10).



3 Chapter Three

The effects of drainage and subsidence on peat aeration at two forested peatlands in Alberta

Forest drainage improves peatland soils for tree growth by increasing aeration of deeper soil layers (Lähde 1969, Mannerkoski 1985), thereby allowing previously shallow tree root systems to expand deeper into the soil (Lieffers and Rothwell 1987). However, conditions present shortly after drainage may be a poor indicator of long term soil conditions. Subsidence alters peat pore characteristics which directly, or indirectly modify soil conditions that regulate tree growth. The purpose of this study was to examine the modifying effect of subsidence on soil properties that regulate soil aeration several years after drainage of two Alberta peatlands.

Soil fauna and plant roots require oxygen for aerobic respiration. Except for a few tolerant species, anoxic conditions reduce tree growth by affecting the hormonal balance, mineral nutrition, and water relations of trees (Kozlowski 1982, 1984, 1986). The concentration of oxygen in soils reflects a balance between the collective biological oxygen demand of all soil biota, and the oxygen supply (Hillel 1980). Well aerated soils allow gaseous exchange between soil air and the atmosphere at a rate that prevents development of oxygen deficiency (Glinski and Stepniewski 1985). Though oxygen demand of soils vary considerably (Hillel 1980), the oxygen concentration required to sustain a particular respiration rate is governed by the rate of oxygen transport from the surface (Glinski and Stepniewski 1985). Some convective gas transport occurs in surface soil layers, however diffusion through soil air-filled pore space is generally considered the primary mechanism of gas exchange in soils (Glinski and Stepniewski 1985). Air-filled pore space is the principal soil property that governs this process (Hillel 1980). Water saturated soils are usually deficient in oxygen, as the rate of diffusive transport of O_2 through water is roughly one tenthousandth of that through air (Glinski and Stepniewski 1985). Existing soil O_2 is rapidly depleted by microbial and root respiration under such conditions.

Peatland drainage improves aeration by reducing soil water content and increasing air-filled pore space through which O_2 can diffuse (Paavilainen

1967). Air-filled porosity after drainage is governed by the interaction of water table levels with the vertical distribution of peat pore sizes (Paavilainen 1967), as these regulate soil water retention and capillary water transport. In Chapter two, I examined the effect of subsidence on pore properties that govern soil water retention and transport in surface peat (0-40 cm depth) at one drained Alberta peatland. Increased bulk density after drainage and subsidence was associated with the loss of large pores, and corresponding increases in the volume of smaller pores. The shift in pore size distribution was related to increased soil water retention, and thus decreased air-filled pore volume at equivalent soil water potentials. However, the study detailed in Chapter two was conducted under controlled soil water conditions. Large differences in mean water table levels between drainage conditions are reported after forest drainage in Alberta (Hillman *et al.* 1990, Rothwell *et al.* 1996). Therefore the magnitude of subsidence effects on air-filled porosity and aeration of surface peat under field conditions is uncertain. Several European studies have reported increased depth of soil aeration after forest drainage (Boggie and Miller 1976, Lähde 1969, 1972, 1974, Lees 1972*a*, 1972*b*, Mannerkoski 1985), however the extent to which subsidence further modifies post-drainage soil aeration is not well documented in the literature.

The objectives of this study were to determine the effects of drainage and subsequent subsidence on air-filled porosity and aeration several years after drainage of two forested peatlands in Alberta. Aeration of soils in this study was evaluated by measuring soil oxygen transport rates, oxygen concentrations, and the depth of the lower limit of the aerated zone. Soil oxygen concentration and the depth of oxygen penetration reflect both oxygen consumption by soil biota, and the rate of oxygen transport from the atmosphere. Though nutrient and thermal conditions affect biological activity and oxygen consumption in peat (Lähde 1969, Lieffers 1988, Silvola *et al.* 1986), this study focused only on physical factors related to pore air-water volume relationships, and their effects on soil aeration. The relationship between soil aeration (oxygen transport, concentration, and depth of penetration), air-filled porosity, and peatland water table levels was examined in drained and undrained areas of both peatlands. Based on the field observations of Rothwell *et al.* (1996), I expected decreased air-filled porosity to be associated with greater soil water retention in drained areas compared to

similar depths in undrained areas. As a result of hypothesized decreases in air-filled porosity, I expected the rate of oxygen transport to be lower in drained areas compared to similar depths in undrained areas. Therefore, I also expected lower soil oxygen concentrations at similar depths, and reduced oxygen penetration as indicated by the depth of the lower limit of the aerated zone in drained areas compared to undrained areas.

3.1 MATERIALS AND METHODS

3.1.1 Study areas and sampling design

This study was conducted at two peatlands drained for forestry in north central (Saulteaux River) and west central (Wolf Creek) Alberta. Description of peatland characteristics and drainage treatments at Saulteaux River is detailed in Chapter two.

The Wolf Creek peatland (53°25' N; 116°01' W) is located approximately 35 km southeast of Edson, Alberta. The Wolf Creek drainage trial is located in a large peatland complex situated along a tributary of Wolf Creek. Peat thickness ranges from 1 to 2 m within the study area (Mugasha 1992). This intermediate fen (Mugasha 1992) supports medium-low density mixed stands of *Picea mariana* (Mill.) B.S.P. and *Larix laricina* (Du Roi) K. Koch.. Understorey vegetation consists of *Betula glandulosa* (Michx.), *Ledum groenlandicum* (Oeder) and *Carex* spp. Dominant moss species include *Sphagnum warnstorfii* (Russ.), *S. angustifolium* (Russ.) Tolf., *Tomenthypnum nitens* (Hedw.) Loeske, *Aulacomnium palustre* (Hedw.) Schwaegr., and *Drepanocladus* spp. Mean annual air temperature at Edson is 2.1 °C (Atmospheric Environment Service 1982a). The area averages 70 frost free days (Atmospheric Environment Service 1982b) and 1170 degree days above 5 °C per year (Atmospheric Environment Service 1982c). Edson receives 572 mm total precipitation annually with 398 mm falling from May through Sept. (Atmospheric Environment Service 1982d). A 60 ha portion of the peatland was drained by the Alberta Forest Service and Forestry Canada in 1987 with 30-, 35-, 40-, and 50-m ditch spacings (Hillman *et al.* 1990). Ditches were 90 cm deep at the time of installation.

The general study design was similar at both peatlands, however some differences in plot location were necessary due to differences in drainage design between Saulteaux River and Wolf Creek. Sampling was done in areas drained

with the narrowest ditch spacing at each peatland (25-m at Saulteaux River, and 30-m at Wolf Creek). In both peatlands, adjacent undrained areas served as controls. A complete-block design was employed at Saulteaux River where five blocks extending from the drained area into the undrained area were established on the boundary of the drainage installation. Sample plots in the drained portion of each block were situated midway between drainage ditches in separate "ditch to ditch" drainage strips. Plots were established in areas with relatively flat micro-topography, intermediate in elevation between hummocks and hollows. Particular care was given to location of undrained plots as previous studies have reported drainage effects downslope from perimeter ditches (Rothwell and Silins 1990, Hillman 1992). Undrained plots were located 80-90 m away from perimeter ditches perpendicular to the direction of groundwater flow based on topographic contours. Undrained plots were located in areas with similar bryophyte composition and micro-topography as drained plots.

Exact duplication of this design was not possible at Wolf Creek as only three 30-m drainage units existed. Two drained plots were established in each of two drainage units, with a fifth plot located in the remaining unit (figure 3-1). Plots within the same drainage unit were located 90-100 m apart to assure sample independence. Location of the undrained area and individual sample plots was based on the same criteria used at Saulteaux River.

3.1.2 Measurements

Soil oxygen transport rates, oxygen concentration, depth of the lower limit of the aerated zone, soil properties, and peatland water table levels were measured in drained and undrained plots in each peatland during the growing seasons of 1991 and 1992. Measurements for each summer season commenced after ground frost recession (approximately mid-June). All measurements described below were conducted approximately once per month in each plot until freeze up in the fall of each year.

3.1.2.1 Soil oxygen transport rates

Measurement of soil oxygen transport in the field is difficult as few suitable techniques exist. In this study, oxygen flux (mass $O_2 \cdot L^{-2} \cdot T^{-1}$) was measured using two techniques (diffusion chamber and platinum

microelectrode) as no single method appeared suitable across a full range of soil moisture conditions (very wet through dry).

3.1.2.1.1 Oxygen flux - "Raney" probe

Oxygen flux and relative oxygen diffusivity was measured at 10, 20, 30, and 40 cm depth using a modified gas diffusion probe after Raney (1949). The "Raney" probe technique measures the rate of oxygen transport from the soil to a diffusion chamber after the establishment of an O_2 concentration gradient between the soil and the chamber. Relative diffusivity describes the ease of oxygen transport through the soil, independent of the oxygen concentration gradient. Oxygen flux reflects the transport rate of oxygen in the presence of a particular concentration gradient, or the oxygen supplying power of the soil (Bruce and Webber 1953, Ghildyal and Tripathi 1987). As the concentration gradient was known from soil oxygen concentration measurements (described below), an approximate solution of Fick's law of diffusion was possible.

Raney (1949) used Taylor's (1949) one dimensional, steady state solution to Fick's law of diffusion [3-1] to estimate the coefficient of diffusion through soil;

$$\log\left(\frac{Co}{Co-C}\right)=\frac{DA}{2.303VL}t \qquad [3\text{-}1]$$

where Co is the atmospheric oxygen concentration, C is the oxygen concentration within the chamber, D is the coefficient of diffusion ($L^2 \cdot T^{-1}$), A is the cross sectional area (L^2) through which diffusion occurs, V is the chamber volume (L^3), L is the diffusive path length (L), and t is time. Equation [3-1] cannot be solved explicitly as the diffusive path length (L) is unknown. However, as log(Co/(Co-C)) is a function of time, the coefficient of diffusion can be determined by the linear relationship between the left hand side of equation [3-1] and time, where D is given by the slope. McIntyre (1962) was critical of the technique as the concentration gradient from the soil to the chamber was unknown. Raney (1949) used the atmospheric O_2 concentration as Co. In the present study the O_2 concentration gradient from the soil to the chamber was known (I used soil O_2 concentration as Co). The coefficient of diffusion is usually presented as the ratio; D/Do (relative diffusivity) where D is the coefficient of diffusion determined through soil, and Do is the coefficient of

diffusion determined through air.

The use of Taylor's solution by Raney (1949) is approximate as steady state theory (static concentration gradient) does not necessarily apply (McIntyre 1962). Though this method, and several other laboratory techniques (Taylor 1949, Gradwell 1961, Bakker and Hidding 1969, Ball *et al.* 1981, Hodgson and McLeod 1989) are essentially transient state methods (concentration gradient changes with time), under quazi-steady state conditions these methods approximate steady state diffusion particularly in the later stages. The use of steady state theory under these conditions should not lead to large errors (McIntyre 1962, Hodgson and McLeod 1989). Using Taylor's original laboratory method, Hodgson and McLeod (1989) assumed quazi-steady state conditions by utilizing the later portion of the diffusion process when the O_2 concentration increase in the diffusion vessel was approximately linear as a function of time. A similar approach was used in this study.

The diffusion probe (65 cm long) was constructed of 1.5 cm dia. copper pipe and brass gas fittings (figure 3-2). The diffusion chamber (1.5 cm dia. x 8.7 cm long) is situated at the bottom of the probe body. The chamber was opened or closed to the soil through diffusion ports at the bottom of the chamber using a sealed valve stem extending through the length of the probe which seats a gas tight seal above the ports. Intake and exhaust lines allowed gas in the diffusion chamber to be flushed with N_2, or cycled through the measurement system. An additional sealed access tube extending from the chamber to the surface housed a thin wire copper-constantan thermocouple for measurement of gas temperature within the diffusion chamber. A Yellow Springs oxygen analyzer (model 51B) and O_2 probe (model 5739) were used to measure oxygen concentration of gas in the diffusion and measurement system. A gas tight measurement chamber was machined from Plexiglas to fit the probe. The measurement system consisted of a series of three-way and one-way air valves connecting the diffusion chamber to the oxygen analyzer and measurement chamber, a gas pumping system, and a compressed N_2 source, all arranged in a closed system. A simple pumping system was constructed using a 10 ml syringe body, one-way air valves, and a rubber balloon (air bladder). The total volume of the chamber and measurement system was kept small relative to that used by Raney (1949) to decrease response time so more measurements could be made.

The probe was inserted into the soil so that the diffusion ports were situated at the target depth. With the diffusion port valve closed and the exhaust valve in the measurement system open, the system was flushed with N_2 gas until no O_2 was detected in the measurement chamber. Nitrogen was used as the counter diffusing gas as it is relatively non-reactive, and of similar molecular weight and diffusivity as oxygen (Taylor 1949, Gradwell 1961, Hodgson and McLeod 1989). During flushing, the syringe body was pumped several times to clear it of O_2. The exhaust and N_2 lines were then closed and the diffusion port was opened to the soil creating a steep O_2 concentration gradient between the surrounding soil and the diffusion chamber. Oxygen from the surrounding soil was allowed to diffuse into the chamber for 1 minute after which the diffusion port was closed and gas in the system was cycled with the syringe pump until a steady O_2 concentration reading was obtained. The diffusion port was then re-opened and the diffusion process was allowed to continue. The O_2 concentration in the diffusion chamber was measured as a function of time at 0, 1, 2, 4, 8, and 12 minutes. Gas temperature within the chamber was measured before the O_2 concentration was determined at 12 minutes. After the measurement series was complete, the probe was pushed further into the soil to the next target depth. Measurements in each plot were performed at 10, 20, 30, and 40 cm depth. As the diffusion chamber was open to the soil during measurements, this technique was limited to measurements above the water table.

Both oxygen flux and relative diffusivity were calculated from the later portion of each diffusion event when the rate of oxygen concentration increase in the diffusion vessel was relatively steady (i.e. nearly linear increase in O_2 concentration with time). The concentration increase in the diffusion chamber was relatively steady between 4 and 12 minutes (figure 3-3). Oxygen flux during this interval was calculated using the ideal gas law after Hodgson and McLeod (1989);

$$Oxygen\ flux\left(\mu g\ cm^{-2}\ \min^{-1}\right)=\frac{\left(V_{12}-V_{4}\right)\times P\times 32\times 10^{6}}{RT\times 1.2668\times 8} \quad [3\text{-}2]$$

where V_{12} and V_4 are the volume (liters) of O_2 in the chamber at 12 and 4 minutes respectively (0.03575 liters x %O_2), P is the atmospheric pressure (I used a mean atmospheric pressure of 0.9098 (atm) for Saulteaux River - 595 m

elevation and Wolf Creek - 975 m elevation), 32 is the molecular weight of O_2 (g mol^{-1}), 10^6 converts g to μg, R is the universal gas constant (0.0821 atm litre mol^{-1} $°K^{-1}$), and T is the chamber temperature (°K), 1.2668 cm^2 is the area of the diffusion ports, and 8 is duration of the diffusion event in minutes. The coefficient of diffusion for each diffusion series was calculated from equation [3-1] utilizing the same diffusion interval (between 4 and 12 minutes). The coefficient of diffusion through air (Do) was determined in the laboratory across a range of air temperatures from 0.9 and 21.5 °C. A linear relationship between gas temperature and Do (Do=0.075+T(0.0003), r^2=0.45) was used to correct D/Do for variation in gas temperature during field measurements. The relationship between D/Do and air-filled porosity was described using the two parameter model of Troeh *et al.* 1982 where;

$$\frac{D}{Do} = \left(\frac{f_a - u}{1 - u}\right)^v \qquad [3\text{-}3]$$

$$\frac{D}{Do} = (f_a)^v \qquad [3\text{-}4]$$

f_a is the soil air-filled porosity (fractional volume), and u and v are empirical parameters. The value of the parameter u from equation [3-3] approached zero in all cases, and was thus dropped from the model [3-4].

3.1.2.1.2 Oxygen diffusion rate (ODR)

A pilot study was conducted late in the 1991 season to determine the suitability of the platinum microelectrode method (Letey and Stolzy 1964) for oxygen diffusion rate (ODR) measurements at Saulteaux River and Wolf Creek. Based on results from the pilot study, ODR was measured during the 1992 season at 10, 20, 30, and 40 cm depth. The technique measures the current produced by the electrochemical reduction of oxygen at the surface of a platinum electrode (cathode) when a standard electrical potential is established between the cathode and a reference electrode (anode). Oxygen in the vicinity of the platinum electrode is rapidly reduced. After some time, the measured current is proportional to the flux of oxygen diffusing from the surrounding soil

to the electrode surface. Oxygen diffusion rate [2] (mass $O_2 \cdot L^{-2} \cdot T^{-1}$) was calculated from measured current (mA) and platinum electrode surface area after Letey and Stolzy (1964). The technique is limited to soils with pH greater than 3-4, and moist enough to cover a thin wire platinum electrode with a film of water during insertion (McIntyre 1970). In this study, the latter requirement limited the reliability of ODR measurements in surface peat during dry periods.

Electrodes were constructed from 0.64 mm diameter platinum wire 10 mm in length soldered to copper leads and fixed with epoxy-resin inside 5 mm diameter stainless steel tubing. An oxygen flux meter described by Poel (1960) was modified to accommodate use of 4 electrodes concurrently. Two Fluke (model 8062A) multimeters were used to monitor applied voltage and resulting current. A single saturated calomel electrode (Fisher 13-639-51), fitted with a cotton wick (Campbell 1980) to improve electrode-soil contact, was used as the anode for all 4 platinum electrodes. Pilot holes were made in the peat to within 5 cm of the target depth using 5 mm dia. steel rods to prevent damage to electrodes during insertion.

Polarograms (amperage-voltage curves) were generated for each electrode to determine the appropriate voltage for ODR measurements (McIntyre 1970). These relationships are necessary to determine if, and over what range of potentials, current is independent of applied voltage (thus primarily dependent on O_2 flux). Voltage was applied in 0.1 V increments from 0.1 to 0.9 volts. Initial tests indicated that measured current was steady after 2-3 minutes. Current at each voltage increment was read after 3 minutes. A 2 minute resting period was used before the next voltage increment was applied. Polarograms were similar to those reported by Campbell (1980) for several eastern Canadian peatland soils. Polarograms were generally similar among sites and drainage conditions (figure 3-4). Based on the shape of the initial polarograms, a constant applied potential of 0.4 volts was selected for all measurements. Polarograms were also re-measured before each ODR measurement over the course of the study as a check on this selected potential. The shape of the amperage-voltage relationships did not change over the course of the 1992 season.

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[2] Note: While oxygen flux is a more precise description of the response variable (McIntyre 1970), the term; oxygen diffusion rate (ODR) is used here for consistency with the literature.

3.1.2.2 Soil oxygen concentration

Soil oxygen concentration profiles were measured in each plot using modified gas sampling wells described by Mukhtar *et al.* (1990). Their design allows gas sampling without creation of pressure gradients from the well to the surrounding soil. As a gas sample is withdrawn from the well, an equivalent volume of water is injected into a bladder within the well, thus gas pressure within the well is unchanged. This prevents sample contamination with soil gas from other horizons, or from the surface during sampling.

Four wells were installed (one at each of 10, 20, 30, and 40 cm depths) in a location central to each plot. Access holes were back filled with dry plaster of Paris and peat to seal them from the surface. The wells were constructed of closed top copper pipe (1.9 cm dia. x 13 cm long) open to the soil at the bottom (located at the target depth). Two copper access tubes (gas sampling and water injection lines) extended from each well to 10 cm above the soil surface (figure 3-5). At the surface, each access tube was sealed from the atmosphere with a 5 cm piece of tygon tubing and a PVC pinch clamp. A rubber balloon was fixed to the water injection line within each well to serve as a water bladder. Two 30 ml plastic syringes were fixed end to end to form a single dual action syringe for sampling. The internal volume of the measurement chamber (previously described) was kept small (3.65 cm^3, including intake and exhaust ports) to minimize the sample volume required for flushing the chamber. In laboratory tests using O_2:N_2 mixtures, a 20-25 ml gas sample was required to completely flush the measurement chamber for O_2 determination. For sampling, one syringe was charged with water and connected to the water injection line with the other syringe connected to the gas sampling line. Pinch clamps were opened and a 30 ml gas sample was withdrawn from the well and injected through the measurement chamber. After measurement, gas was re-injected into the well, and the water was withdrawn.

After sampling, the O_2 concentration of gas in the well equilibrates over time with that of the surrounding soil. Ray *et al.* (1987) observed that a maximum gas equilibration time of three days was required in peat soils, while Boggie (1977) reported up to two weeks for equilibration of water samples. The monthly sampling protocol used in this study was well in excess of maximum times reported by these and other authors. The modified wells used in this

study improved on the design described by Mukhtar *et al.* (1990) by allowing wells to remain charged with gas during the equilibration period. As a result, direct measurement of gas phase equivalent O_2 concentration below the water table was possible with these wells.

3.1.2.3 Aerobic limit depth

The position of the aerobic limit (defined by Lähde (1969) as the lower limit of the aerated zone) was measured by observing the depth of rust formation on mild steel rods inserted into the peat (Carnell and Anderson 1986). While soil oxygen concentrations can change rapidly in response to changes in aeration conditions (Magnusson 1992, 1994), zones of oxidized or reduced iron form more slowly on the surface of steel rods (Carnell and Anderson 1986). Thus the aerobic limit reflects the maximum depth of oxygen penetration into soils, integrated over a longer period of time. As with ODR measurements, a pilot study was conducted during the 1991 season to determine the suitability of this technique. Based on results from this study, aerobic limit depth was measured during the 1992 season using this method. Mild steel welding rods 5 mm diameter and 1.3 m in length were sanded to a bright metal finish before installation. One rod was inserted to a depth of 1 m in a location central to each plot. Rods were removed after a 4 week incubation period and gently cleaned with a moist cloth. Two general patterns of rusting were observed. Where the water table was near to the soil surface (< -50 cm), a sharp transition from orange/brown iron oxide to flat grey reduced iron was observed. Where the water table was lower, discontinuous "patches" of iron oxide extended lower into the reduced iron zone. Depth from the soil surface to the deepest occurrence of iron oxide was chosen as the position of the aerobic limit (Carnell and Anderson, 1986). Rods were sanded with emery cloth to remove all traces of oxidation/reduction and re-inserted into the soil.

3.1.2.4 Soil sampling

Soil water content, bulk density, solid volume fraction, and air-filled porosity were measured by sampling with a modified peat box sampler after aeration measurements were complete in each plot. The sampler is a 3 sided steel box with sharpened edges that yields an 8 cm x 8 cm x 50 cm long peat column (Jeglum et al 1992). The peat surface was pre-cut with a serrated long-

blade knife along three sides of the box samplers edges to guard against peat compression as the sampler was inserted into the soil. Though some minor compression may have occurred during sampling the relatively low bulk density peat found in undrained areas, the effect of such compression would tend to minimize differences between high-density drained peat, and low-density undrained peat. As a consequence, compression during sampling was not considered a major source of error in this study. As in the previous study, the top of the live moss layer was assumed to represent the peat surface. A peat column was extracted from the area immediately adjacent to the location of ODR and 'Raney probe' measurements in each plot. The core was sub-sampled into depth increments of 0-10, 10-20, 20-30, and 30-40 cm. Samples from increments below the water table were not retained. Peat samples were placed in plastic bags and returned to the laboratory for water content and bulk density determinations. Samples were weighed wet, dried in a forced air oven at 70 °C until dry and then re-weighed. Solid volume fraction of each increment was calculated from bulk density and mean particle density previously measured at these peatlands (data for Saulteaux River are presented in Chapter two). Air-filled porosity (f_a) of each depth increment was calculated as $f_a = 1 - (\theta v + (\text{bulk density}/\text{particle density}))$. Selected soil physical and chemical properties for Wolf Creek were measured using methods described in Chapter two, and are presented in Appendix 3. As little variation in particle density was evident in Chapter two, particle densities measured from frozen peat cores (Chapter two; table 2-1, and Appendix 3) were used in the calculation of air filled porosity in the present study.

3.1.2.5 Water table levels and precipitation

The water table level in each plot was measured using wells constructed of perforated PVC pipe (3.2 cm dia. x 150 cm long) installed into augured holes (130 cm deep) in a location central to each sample plot. The water level was determined by noting the depth of the wetted portion on a steel tape measure inserted into each well. In addition to plot measurements, continuous measurement of ground water levels was performed using water level recorders (Stevens F type) in one drained and undrained plot at each peatland. Precipitation was monitored using a tipping bucket rain gauge and a data

logger at a meteorological station established within the drained area at each peatland.

3.1.3 Statistical analysis

Differences in water table position, soil characteristics, and measures of aeration among drainage conditions and depths were analyzed using ANOVA procedures for complete-block designs (Milliken and Johnson 1984). Soil O_2 concentration data were analyzed using repeated measures ANOVA. Separate analyses were conducted for each year individually as all data were not complete for both study years (ODR and aerobic limits were measured in 1992 only). Soil sampling and "Raney" probe measurements were performed above the water table only; thus these data were unbalanced with respect to drainage condition by depth. For ANOVA procedures, only those depth increments which were balanced across drainage conditions were included in the analysis (0-30 cm depth for Saulteaux River 1991 and 1992; and 0-20 cm depth for Wolf Creek 1991, and 0-30 cm depth for Wolf Creek 1992). Monthly sampling periods were considered random observations of drainage and depth effects in each peatland by year combination, though drainage and depth effects were tested only against their interaction with the random factor "plot" (Appendix 4). Data for monthly sampling periods are presented in Appendix 5.

Aeration profiles above the water table level (i.e. water table level as the datum) were analyzed using non-linear regression techniques for the entire data set. Though the water table level is not a stationary datum, the effects of differential capillary rise between drainage conditions on aeration was examined in this way. Non-linear functions were selected (based on general form and estimation properties) to describe the trends evident for each measure of aeration (Ratkowsky 1989). Tests for coincident regressions were performed according to Zar (1974).

3.2 RESULTS

The summer of 1992 was somewhat drier than that of 1991 at both peatlands. Differences in precipitation and water table levels between 1991 and 1992 were greater at Wolf Creek than at Saulteaux River. Summer precipitation (June-Sept.) at Saulteaux River was 273 mm in 1991 and 254 mm in 1992, while Wolf Creek received 361 mm and 258 mm precipitation during the same

periods. Long term average precipitation (1961-90) for these months are 296 mm and 380 mm for Saulteaux River and Wolf Creek respectively (Atmospheric Environment Service 1993). Water table levels declined throughout the summer in 1991 and 1992 at both peatlands (Figure 3-6). Mean seasonal water table levels generally reflected differences in seasonal precipitation between years for both peatlands. At Saulteaux River, mean water table levels were generally similar between years, while at Wolf Creek mean water table levels were lower during 1992 in both drained and undrained areas. The highest and lowest mean water table levels were observed at Wolf Creek during 1991 and 1992, respectively. Mean water table levels at the mid-point between ditches within drained areas were 30-40 cm below that of undrained areas during both years at Saulteaux River and Wolf Creek ($p<0.01$).

3.2.1 Soil properties

Soil moisture and pore properties generally reflected differences in water table levels between drainage conditions, and years for both peatlands. Complete results of analysis of variance for soil properties and aeration measurements are presented in Appendix 4. Despite lower water table levels in drained areas, mean soil water content in drained areas was greater than in undrained areas of both peatlands (table 3-1). However, these differences were significant only during the wetter summer of 1991 ($p<0.027$ at Saulteaux River, and $p=0.029$ at Wolf Creek). Differences in mean soil water content between drainage conditions were associated with differences in mean water table levels. The greatest and least difference in mean soil water content between drainage conditions occurred at Wolf Creek in 1991 (0.29 θv) and 1992 (0.13 θv) respectively, where the highest and lowest mean water table positions were observed. Soil water content increased with depth in both peatlands and drainage conditions ($p<0.001$). The greatest difference in water content between drained and undrained peat during both seasons was observed in the surface layer (0-10 cm depth) where drained peat retained 52% more water relative to that of undrained peat at Saulteaux River and 39% more at Wolf Creek (figure 3-7). Relative differences in mean water content between drainage conditions decreased with depth to 19% at Saulteaux River and 22% at Wolf Creek for 20-30 cm depth increments. Significant interactions between drainage condition and depth were not evident for water content at either peatland. Mean seasonal

soil water content was greater in both drainage conditions during 1991 than in 1992 at both peatlands, though differences between years were greatest at Wolf Creek ($p=0.056$ at Saulteaux River, $p=0.003$ at Wolf Creek).

Mean peat bulk density within drained areas was consistently greater than in undrained areas (table 3-1) of both peatlands ($p<0.001$). Bulk density increased with depth (figure 3-7) in both peatlands and drainage conditions ($p<0.028$). Bulk density of surface peat (0-10 cm depth) in drained areas was 2.5 to 3 times greater than that of undrained peat in both peatlands. Relative differences in bulk density between drainage conditions decreased with depth to 70-100 % in the 20-30 cm depth increments at both peatlands. Significant interactions between drainage condition and depth were not observed, except at Wolf Creek in 1992 ($p=0.003$) where relative differences between drainage conditions decreased to 37% at 30-40 cm depth. Bulk density did not vary significantly between years at either peatland.

Mean solid volume fraction was consistently greater in drained peat than in undrained peat ($p<0.001$) at both peatlands (table 3-1). Solid volume fraction increased with depth in both drainage conditions ($p<0.001$). Though not shown in figure 3-7, relative differences in solid volume fraction by drainage condition and depth were similar to those observed for bulk density. Consistent with observations of peat bulk density, the solid volume fraction of peat did not vary between 1991 and 1992 at either peatland.

Differences observed in air-filled porosity between drainage conditions, depths, and years generally reflected the inverse relationship of air-filled porosity and soil water content. Despite lower water table levels in drained areas, air-filled porosity of drained peat was less than that of undrained peat (table 3-1). Differences in air-filled porosity between drainage conditions were much greater during the wetter summer of 1991 ($p=0.005$ at Saulteaux River, and $p=0.009$ at Wolf Creek) than during 1992 ($p=0.129$ at Saulteaux River, and $p=0.168$ at Wolf Creek). Air-filled porosity decreased with depth (figure 3-7) at both peatlands ($p<0.001$). Unlike the other soil properties, relative differences in air-filled porosity between drainage conditions increased with depth (figure 3-7). In the surface 0-10 cm layer, undrained peat contained 10-30% greater air-filled pore volume than drained peat. Relative differences between drained and undrained peat increased to approximately 150-200% at 20-30 cm depth. Significant interactions between drainage and depth were not evident at either

peatland. Mean air-filled porosity was greater in both drainage conditions during the drier summer of 1992 than during 1991 ($p=0.066$ at Saulteaux River, and $p=0.003$ at Wolf Creek). As with peat water content, differences in air-filled porosity between 1991 and 1992 were greater at Wolf Creek where larger differences in both water table position and water content between years were observed.

Air-filled porosity varied in response to seasonal water table fluctuation in both drainage conditions. Though quite variable, linear relationships between depth of water table from the soil surface (both years combined) and air-filled porosity were observed in each peatland and drainage condition (Table 3-2). These relationships were different between drained and undrained areas ($p<0.003$ for all depth increments in both peatlands). Based on the slope of these relationships, air-filled porosity within drained areas was less sensitive to water table variation than in undrained areas of both peatlands. Differences between drainage conditions in air-filled porosity profiles above the water table surface were also observed (Figure 3-8). Air-filled porosity decreased as the distance between the measurement point and the water table surface decreased. This relationship was described by a three parameter empirical model; $y=a+bx^c$ (Ratkowsky 1989) where y and x are the distance above the water table, and air-filled porosity, respectively. These relationships were different for drained and undrained areas of each peatland during both 1991 and 1992 ($p<0.001$). In undrained areas of both peatlands, air-filled porosity decreased very rapidly from 0.8-0.9 approximately 10-30 cm above the water table to near-zero values 0-8 cm above the water table. Despite much lower water tables in drained areas, a similar range of reduction in air-filled porosity was observed. However, based on the value of the y-intercept (a), air-filled porosity declined to near-zero values 11-22 cm above the water table in drained areas.

3.2.2 Oxygen flux

Oxygen flux measured with the "Raney" probe was affected by drainage condition and depth, and varied in response to differences in mean water table levels between years. Mean oxygen flux was generally greater in drained areas than in undrained areas, though differences between drainage conditions were significant at Wolf Creek only. During 1991, mean oxygen flux at Wolf Creek

was 82.1 and 75.2 μg cm^{-2} min^{-1} in drained and undrained areas, respectively (p=0.014), while in 1992, mean oxygen flux was 118.4 and 102.7 μg cm^{-2} min^{-1} (p=0.004) for the same drainage conditions. Differences between drainage treatments (10 to 30 cm depth) were not evident at Saulteaux River (p=0.141 in 1991, and p=0.914 in 1992). Oxygen flux decreased with depth in both drainage conditions at each peatland (p<0.003). A rapid reduction in mean oxygen flux occurred within the uppermost 30 cm in the drained area of Wolf Creek, with little subsequent reduction below this level (figure 3-9), while oxygen flux declined more steadily from 10 to 40 cm depth at Saulteaux River. Interactions between drainage condition and depth were not evident for oxygen flux except at Saulteaux River in 1992 (p=0.040). Mean oxygen flux was greater during 1992 than during 1991 in both drainage conditions at Wolf Creek (p=0.003). No difference in oxygen flux between years (10 to 30 cm depth) was observed at Saulteaux River (p=0.234).

Differences in oxygen flux profiles above the water table were also evident between drainage conditions at both peatlands (figure 3-10). An approximately linear decrease in oxygen flux was observed as the distance between the water table and the measurement point decreased. However, the form of the linear relationship differed between drainage conditions (p<0.001 for both peatlands and years). In undrained areas, oxygen flux decreased to near-zero values approximately 1-6 cm above the water table, while in drained areas, near-zero values (based on y-intercepts) were observed 6-38 cm above the water table. Differences in the value of the y-intercept between drained and undrained areas increased as mean water table levels decreased. This was particularly evident at Wolf Creek where little difference in y-intercepts between drainage conditions was observed during the wet summer of 1991. However, during the drier summer of 1992, oxygen flux in the undrained area approached zero approximately 6.4 cm above the water table, while near-zero values were observed 38.0 cm above the water table in the drained area.

3.2.3 Relative diffusivity

Relative diffusivity (D/Do) was related to air-filled porosity in both drainage conditions at Saulteaux River and Wolf Creek (figure 3-11). The relationship for each drainage condition was similar between years (p>0.230), thus data for both years were combined. Though the relationship between

D/Do and air-filled porosity was quite variable at both peatlands (r^2 varied from 0.42-0.76; $p<0.001$ for both peatlands and drainage conditions), the form of the relationship differed between drained and undrained areas ($p<0.001$). In drained areas of both peatlands, a nearly linear relationship between relative diffusivity and air-filled porosity was observed, whereas a curvilinear relationship was evident in undrained areas. Very high relative diffusivities (i.e. greater than 0.8) were observed at high air-filled porosities (0.7 to 0.9) in both drained and undrained areas of both peatlands. However, where oxygen diffusion was restricted (i.e. D/Do less than 0.1 to 0.2), large differences in air-filled porosity between drainage conditions was evident in both peatlands. For example, at D/Do = 0.1, air-filled porosities in drained areas were approximately 16% by volume at Saulteaux River and 24% at Wolf Creek, compared to 43% and 44% in undrained of both peatlands respectively.

3.2.4 Oxygen diffusion rate (ODR)

The effects of drainage and depth on ODR were generally similar to oxygen transport rates measured using the diffusion chamber method, though differences between years observed with the "Raney" probe could not be confirmed as ODR was measured only during 1992. Mean ODR (10-40 cm depth) was 2.80 and 1.53 x 10^{-8} g cm^{-2} min^{-1} in drained and undrained areas of Saulteaux River respectively ($p=0.040$), while at Wolf Creek, mean ODR was 2.77 and 2.35 x 10^{-8} g cm^{-2} min^{-1} ($p=0.071$) for both drainage conditions respectively. Oxygen diffusion rate decreased with depth in drained and undrained areas of both peatlands ($p<0.009$). In undrained areas, the greatest reduction in ODR occurred between 10 and 20 cm depth at Saulteaux River, and between 10-30 cm at Wolf Creek (figure 3-12). Low ODR values at 10 cm depth in drained areas of both peatlands was probably a result of poor electrode to soil contact in dry, surface peat. Air-filled porosity at this depth was high in both peatlands, and a similar response was not evident in "Raney" probe measurements. Thus, the significant drainage by depth interaction observed at both peatlands ($p<0.009$) probably reflected technique failure at low soil water contents, and not differential response of oxygen transport rates between drainage conditions with depth.

Differences in ODR profiles above the water table were also evident between drainage conditions at both peatlands (figure 3-12). Oxygen diffusion

rate decreased rapidly as the distance between the measurement point and the water table surface decreased. This relationship was described using a three parameter empirical model (Ratkowsky 1989); $y=a+(b-a)c^x$, where y and x are the distance above the water table, and ODR, respectively. In undrained areas ODR decreased approached zero 7-8 cm below the water table (based on y-intercept; parameter b), while near-zero values were observed 1-39 cm above the water table in drained areas of both peatlands. Though the ODR profile was quite variable in the drained area of Saulteaux River, differences in the height of the inflection point above the water table between drainage conditions appeared greater at Wolf Creek, where differences in water table levels between drainage treatments were greater.

3.2.5 Soil oxygen concentration

Though highly variable within each season, soil oxygen concentrations differed among drainage conditions, depths, and years at both peatlands. Compared to oxygen concentrations in undrained areas, mean oxygen concentrations were generally greater in drained areas of both peatlands (differences were not significant at Wolf Creek during 1991). Mean oxygen concentration at Wolf Creek was 15.3 and 13.8% O_2 in drained and undrained areas respectively ($p=0.383$) during 1991, while in 1992, mean oxygen concentration was 17.4 and 14.5% O_2 ($p=0.031$) for the same drainage conditions. At Saulteaux River, mean oxygen concentration was 16.7 and 14.1% O_2 in drained and undrained areas respectively ($p=0.042$) during 1991, while in 1992, mean oxygen concentration was 17.4 and 15.0% O_2 ($p=0.008$) for the same drainage conditions. Soil oxygen concentration decreased with depth (figure 3-13) in both drainage conditions ($p<0.001$) from near ambient concentrations (20.9%) at 10 cm depth to 10-12 % O_2 at 40 cm depth at both peatlands. Soil O_2 concentrations in drained and undrained areas were similar at 10 cm depth, differed at 20 and 30 cm depth, and were similar again, at 40 cm depth. However, the interaction of drainage and depth effects was significant only at Saulteaux River in 1991 ($p=0.014$). Mean soil oxygen concentration increased slightly from the wetter summer of 1991 to 1992 in both peatlands and drainage conditions, though differences between years was significant only at Wolf Creek ($p=0.022$) where differences in water table position and soil moisture conditions between years was greatest.

As with the other measures of aeration, differences in O_2 concentration profiles above the water table were observed between drainage conditions (figure 3-14). These relationships were described by a two parameter empirical model (Ratkowsky 1989); $y=a+(1/(1+bx))$, where y and x are the distance above the water table, and O_2 concentration respectively. Oxygen concentrations initially remained near ambient levels as the distance from the measurement point to the water table surface decreased, after which a rapid decline in O_2 concentrations near the water table surface was observed in both drainage conditions. In undrained areas of both peatlands, this rapid decrease occurred from 2 cm above the water table to 18 cm below the water table (based on the value of the horizontal asymptote; parameter a), while in drained areas, a similar decrease occurred 4-35 cm above the water table. Differences in non-linear regressions between drainage conditions were evident ($p<0.001$) at both peatlands during 1991 and 1992. At Wolf Creek, the inflection point in O_2 concentration occurred closer to the water table (both drainage conditions) during the wetter summer of 1991 than in 1992. No obvious difference in the position of the inflection points between years was evident at Saulteaux River. A slight increase in O_2 concentration below the water table was often observed during individual plot measurements in undrained areas, however this trend was evident on a seasonal basis only at Saulteaux River during 1992.

3.2.6 Aerobic limit depth

During 1992, the mean aerobic limit depth as measured by oxidation of mild steel rods in drained and undrained areas of Saulteaux River was 44.3 and 22.6 cm respectively ($p<0.001$), while at Wolf Creek, aerobic limits occurred at 36.4 and 27.1 cm depths for the same drainage conditions respectively ($p=0.029$). However, unlike the other measures of aeration, differences between drainage conditions were greatest at Saulteaux River. Aerobic limit depth was linearly related to water table variation within drained and undrained areas of both peatlands ($p<0.043$), though the range of variation in both water table level and aerobic limit depth was much greater at Saulteaux River than at Wolf Creek (figure 3-15). As with the other measures of aeration, the aerobic limit occurred 0-10 cm above the water table surface in undrained areas, compared to 30-40 cm above the water table in drained areas. Though the relationship was weak at Wolf Creek, the distance between the water table

level and the aerobic limit increased as the water table level decreased in both drainage conditions at Saulteaux River.

3.3 DISCUSSION

3.3.1 Air-filled porosity

Drainage and subsidence at Saulteaux River and Wolf Creek were clearly associated with a reduction in air-filled porosity of surface peat. In contrast, Boggie (1977), and Paavilainen (1967) both reported that lower water table levels after drainage were associated with increased air-filled porosity. The observation of reduced post-drainage air-filled porosity in the present study constitutes evidence of a substantial subsidence effect as water table levels were much lower in drained compared to undrained areas. Given these differences in water table levels, even a finding of similar air-filled porosities between drainage conditions would have indicated alteration of air-filled porosity by subsidence. These results suggest that very low water table levels may be required to maintain high air-filled porosities after drainage and subsidence. This statement is supported by predicted air-filled porosity profiles as a function of water table depth (figure 3-16) based on relationships reported in table 3-2. For example, to lower air-filled porosity to a minimum of 0.1 within the top 30 cm of soil surface, water tables in undrained areas would need to be at least 32-35 cm below the surface. In contrast, within drained areas of both peatlands, a minimum water table level of approximately 55-60 cm would be required to achieve the same minimum air-filled porosity. The association between increased peat density (bulk density and solid volume fraction), increased soil water retention, and reduced air-filled porosity supports the hypothesis that a reduction in air-filled porosity can be expected with post-drainage subsidence of forested peatlands.

In general, air-filled porosity in drained areas was also less sensitive to water table variation than in undrained areas. This result is consistent with the observation in Chapter two of a lower proportion of large, non-capillary pores (i.e. drain easily under gravity) in drained areas after subsidence, and thus greater water retention and/or capillary transport from the water table. Paavilainen (1967) observed a decrease in sensitivity of air-filled porosity to water table fluctuation in deeper, more humified peat. In the present study

however, a similar reduction in sensitivity of air-filled porosity to water table variation was associated with greater bulk density due to subsidence. In undrained areas, a wide range of air-filled porosities were produced by a narrow range of water table variation (figure 3-16), while in drained areas, the opposite was true. Differential air-filled porosity profiles above the water table observed between drainage conditions probably reflected differences in the thickness of the capillary zone due to post-drainage subsidence.

3.3.2 Peat aeration

Despite lower air-filled porosity in drained areas, soils were generally better aerated within the surface 10-40 cm, and were aerated to deeper levels than in undrained areas. These results were contrary to my expectations for oxygen transport rates, and depth of aeration based on reductions in air-filled porosity after drainage and subsidence. However, higher levels of aeration (all measures) in drained areas were associated with lower water table levels in these areas.

Though drainage and subsidence reduced air-filled porosity of surface peat, air filled porosity was not reduced to a critical level that severely restricted aeration within the uppermost 40 cm. A possible explanation for this finding is that greater air-filled pore continuity may be associated with smaller mean pore sizes after subsidence. The distribution of air-filled pore volume among different pore sizes influences the likelihood of continuous pore pathways into soils, and their tortuosity (Currie 1984). In higher density drained peat, air-filled pore volume was probably distributed among many small pores. Though such pore pathways would be tortuous, the probability of continuous pore pathways would be great owing to the large number of air-filled pores. Conversely, similar pore volumes in undrained areas were probably distributed among fewer large pores, thus a lower likelihood of continuous pore pathways would have existed (i.e. the number of occluded or discontinuous pore pathways were probably greater). This supposition is supported by the observation of low relative diffusivities (i.e. 0.1 % D/Do) at air-filled porosities between 0.16-0.24 in drained areas compared to 0.43-0.44 in undrained areas. Similar findings have been reported in compacted and uncompacted mineral soils (Currie 1984, McAffee 1989). At higher air-filled porosities, a near linear increase in D/Do with air-filled porosity was observed

in drained areas, while D/Do in undrained areas increased more rapidly (i.e. highly non-linear). This latter observation supports the assertion of more tortuous air-filled pore pathways after subsidence. These findings suggest that critical air-filled porosities may vary among soils. Though the 10% air-filled porosity suggested by Päivänen (1973) as an approximate minimum for adequate aeration is not refuted by the present study, this figure may vary between different peat types depending on the size distribution of air-filled pores.

Rather than a reduction of aeration of surface peat (as hypothesized), subsidence was associated with reduced aeration response to water table variation in deeper peat (i.e. restriction of maximum aeration depth despite additional reduction in water table levels). By increasing the height of the capillary zone above the water table, an important effect of subsidence may be to restrict aeration of deeper layers. The correspondence of minimum aeration values (O_2 transport and concentration) with air-filled porosity profiles above the water table support this conclusion. In general, O_2 flux, ODR, and O_2 concentration declined to their respective minimum values in the immediate vicinity of the water table in undrained areas, while similar low values were observed approximately 15-40 cm above the water table in drained areas. Similar differences in O_2 concentration and ODR profiles above the water table between coarse and fine textured mineral soils were observed by Kristensen and Enoch (1964).

Though some deviations from these general patterns were observed in O_2 concentration profiles and aerobic limit depths, these probably reflect trends under nearly anaerobic conditions. Oxygen concentration increased slightly below the depth at which the minimum O_2 transport values were observed. This observation probably indicates both minimal O_2 consumption, and a source of oxygen below this depth. Both Pyatt and Smith (1983) and Magnusson (1992, 1994) suggested dissolved oxygen in slowly moving ground water as this O_2 source. However, oxygen at these depths is probably of limited value to tree roots as O_2 transport rates to root surfaces would probably be insufficient to support sustained respiration. Aerobic limits also occurred deeper and closer to the water table surface (particularly when water tables were deep) than did minimum values of O_2 flux, ODR, and O_2 concentrations. As aerobic limit depth reflects the maximum depth of oxidizing conditions integrated over long periods

of time (i.e. 30 days), the aerobic limit was probably less sensitive to gradients from oxidizing to reducing conditions with depth, than were O_2 concentration or O_2 transport variables. Lähde (1969) observed a similar low sensitivity of aerobic limit depth to subtle gradients in reducing conditions with depth, and concluded that the aerobic limit indicates the depth at which anaerobic, or completely reducing conditions prevail. Thus aerobic limit depth is probably a better indication of the switch from weakly reducing to strongly reducing conditions, rather than an indicator of the depth of "effective" aeration for root growth.

The relationships between water table level, air filled porosity, and measures of aeration observed in this study were based on observations during periods of generally stable, or receding water table levels. However, variation in the relationships between water table levels, air filled porosity, oxygen transport rates, and oxygen concentrations might be expected between periods of rising and falling water table levels due to hysteresis effects on soil water content. During periods of rising water table levels, air filled porosities would probably be greater, and therefore oxygen transport rates and concentrations might be greater than those observed in the present study. Lähde (1969) reports a close correspondence of aerobic limit depth with rising water table levels, while aerobic limits occurred consistently above the water table level during periods of water table recession. Similar hysteresis effects might be expected in the peatlands considered in this study. However, as receding water table levels were much more common than rising water table levels during 1991 and 1992 at both peatlands, the relationships observed in this study were probably representative of aeration conditions over a large proportion of both summer seasons at Saulteaux River and Wolf Creek.

3.4 CONCLUSIONS

Soil aeration was improved in surface peat after drainage of forested peatlands at Saulteaux River and Wolf Creek. Increased peat bulk density and soil water retention associated with post-drainage subsidence resulted in reduced air-filled porosity from 0-40 cm depth. Contrary to my expectations however, reduced air-filled porosity was not associated with reduced soil aeration. Though improved aeration in drained areas was related to lower post-drainage water table levels, greater O_2 transport at low air-filled porosities

in drained areas may have resulted from increased continuity of air-filled pores. A shift from few, large air-filled pores before drainage, to greater numbers of smaller air-filled pores after drainage and subsidence may be the mechanism involved in this increase. By increasing the thickness of the capillary zone above the water table, an important effect of post-drainage subsidence may be the reduction of aeration response to water table fluctuation in deeper peat layers, rather than a reduction of aeration in surface peat.

3.5 LITERATURE CITED

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Table 3-1 Mean (0-40 cm depth) seasonal soil water content (θ), bulk density (ρb), air-filled porosity (f_a), and solid volume fraction (S) in drained and undrained areas of Saulteaux River and Wolf Creek during 1991 and 1992. Values in brackets indicate 1 standard error of the mean.

		θ (fract.vol)	ρb (Mg m^{-3})	f_a (fract.vol)	S (fract.vol)
Saulteaux River					
1991	Drained	0.627 (0.029)	0.135 (0.004)	0.282 (0.031)	0.090 (0.003)
	Undrained	0.439 (0.040)	0.056 (0.005)	0.524 (0.043)	0.038 (0.003)
1992	Drained	0.579 (0.027)	0.127 (0.004)	0.336 (0.029)	0.085 (0.002)
	Undrained	0.386 (0.034)	0.056 (0.005)	0.577 (0.036)	0.038 (0.003)
Wolf Creek					
1991	Drained	0.622 (0.029)	0.124 (0.006)	0.296 (0.033)	0.082 (0.004)
	Undrained	0.335 (0.033)	0.029 (0.002)	0.649 (0.034)	0.017 (0.001)
1992	Drained	0.526 (0.033)	0.126 (0.006)	0.390 (0.037)	0.084 (0.004)
	Undrained	0.394 (0.036)	0.052 (0.006)	0.574 (0.039)	0.032 (0.004)

Note: Means include all available data. Undrained means contain more observations above 20 cm depth than below, thus undrained means are biased towards surface peat conditions.

Table 3-2 Linear relationships between water table level in cm (Wt) and air-filled porosity (fa - fractional volume basis) in drained and undrained peat at four depth intervals at Saulteaux River and Wolf Creek. Values in brackets indicate r^2. P values reflect tests for coincident regressions between drained and undrained areas.

Depth (cm)		Saulteaux River	Wolf Creek
0-10	Drained	Fa = 0.2950 - 0.0049 Wt (0.54)	Fa = 0.4441 - 0.0040 Wt (0.33)
	Undrained	Fa = 0.5273 - 0.0096 Wt (0.42)	Fa = 0.6818 - 0.0044 Wt (0.54)
	Dr vs Undr	p<0.0001	p<0.0001
10-20	Drained	Fa = 0.0442 - 0.0044 Wt (0.29)	Fa = 0.1086 - 0.0050 Wt (0.33)
	Undrained	Fa = -0.0604 - 0.0187 Wt (0.43)	Fa = 0.3477 - 0.0070 Wt (0.34)
	Dr vs Undr	p<0.0001	p<0.0001
20-30	Drained	Fa = -0.1342 - 0.0046 Wt (0.39)	Fa = -0.0558 - 0.0036 Wt (0.29)
	Undrained	Fa = -0.2602 - 0.0157 Wt (0.45) *	Fa = -0.0646 - 0.0109 Wt (0.14) *
	Dr vs Undr	p<0.0001	p<0.0001
30-40	Drained	Fa = -0.0969 - 0.0030 Wt (0.30)	Fa = -0.0681 - 0.0023 Wt (0.31)
	Undrained	Data not collected	Fa = -1.5292 - 0.0356 Wt (0.55) *
	Dr vs Undr	N/A	p=0.0034

* Not significant at p=0.05

Figure 3-1 Drainage design and location of sample plots at Saulteaux River and Wolf Creek.

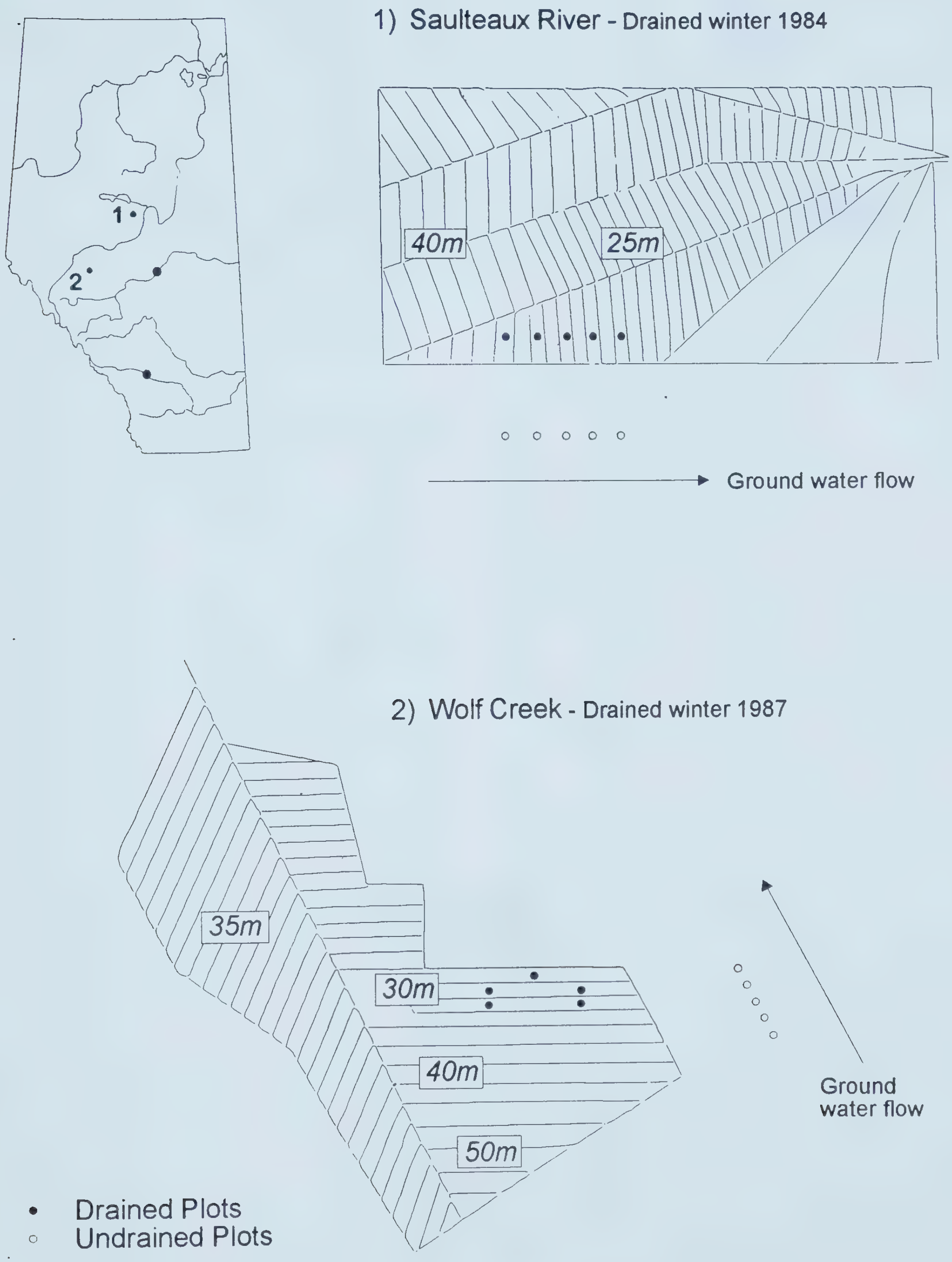


Figure 3-2 Design of "Raney" probe and measurement system.

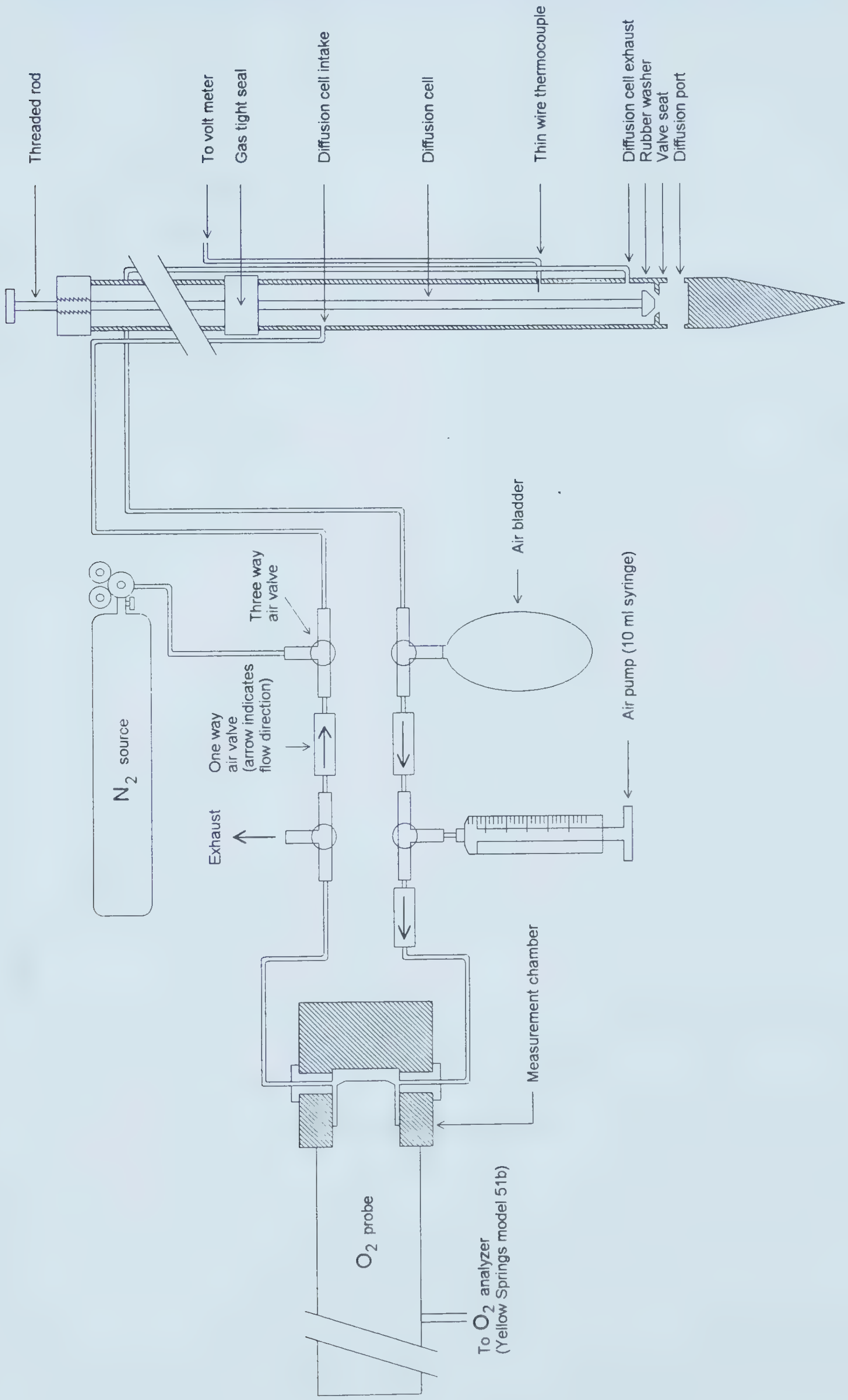


Figure 3-3 Mean oxygen concentration (0-40 cm depth, 1991 and 1992) as a function of time for drained and undrained areas of Saulteaux River and Wolf Creek. Error bars indicate one standard error of the mean.

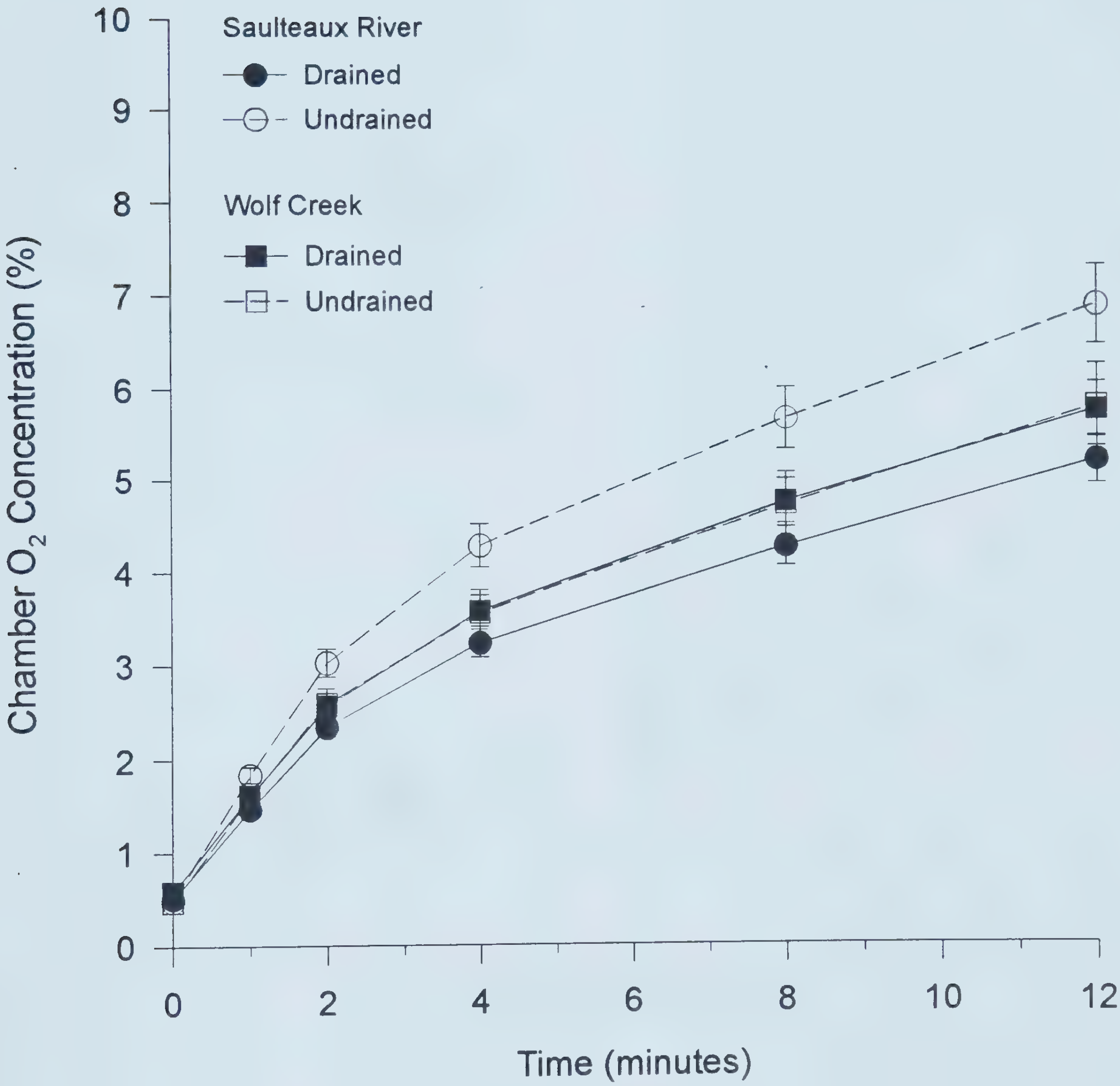


Figure 3-4 Mean seasonal polarograms (measured current as a function of applied voltage) using the platinum micro-electrode method for drained and undrained areas of Saulteaux River and Wolf Creek. Error bars indicate one standard error of the mean.

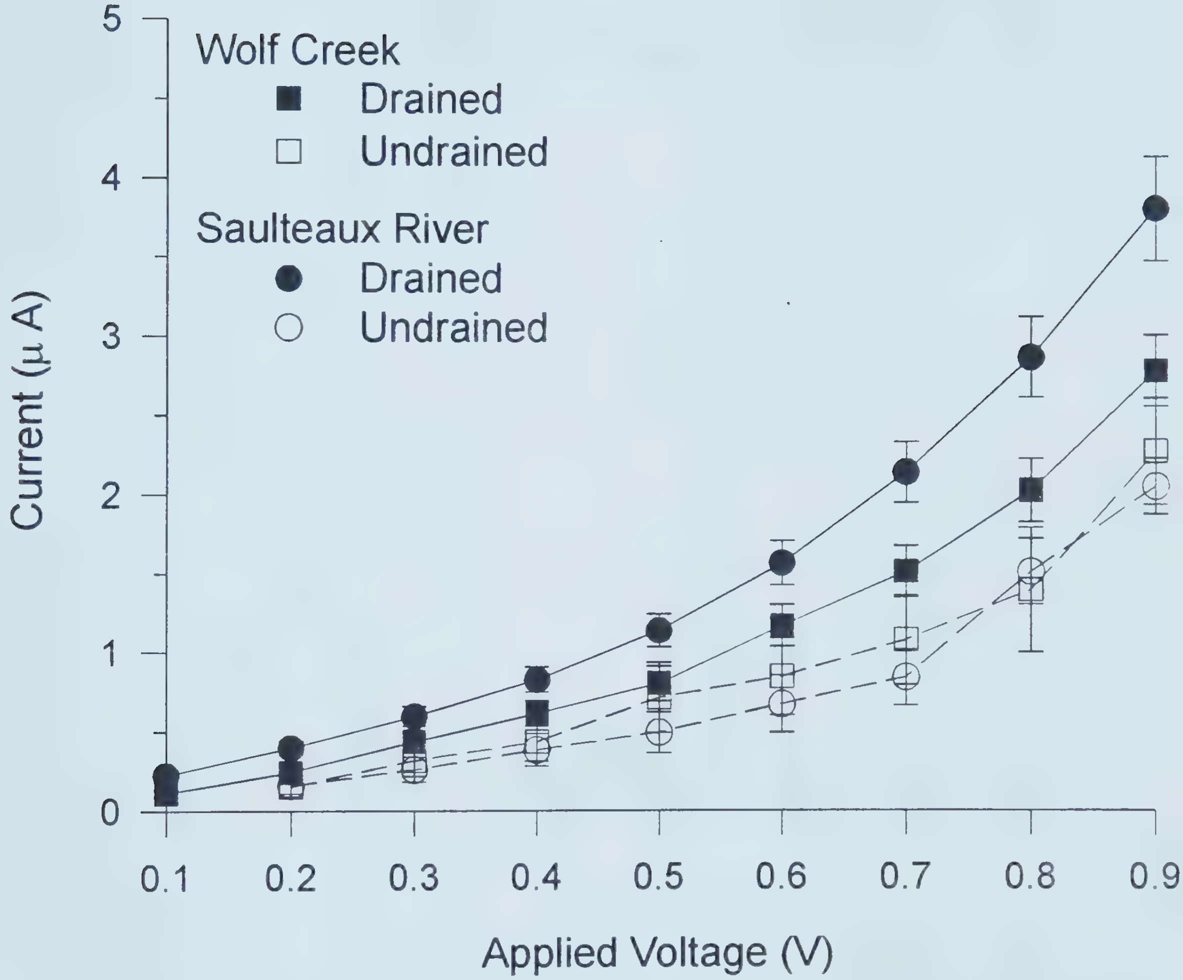


Figure 3-5 Design of gas sampling wells and measurement system.

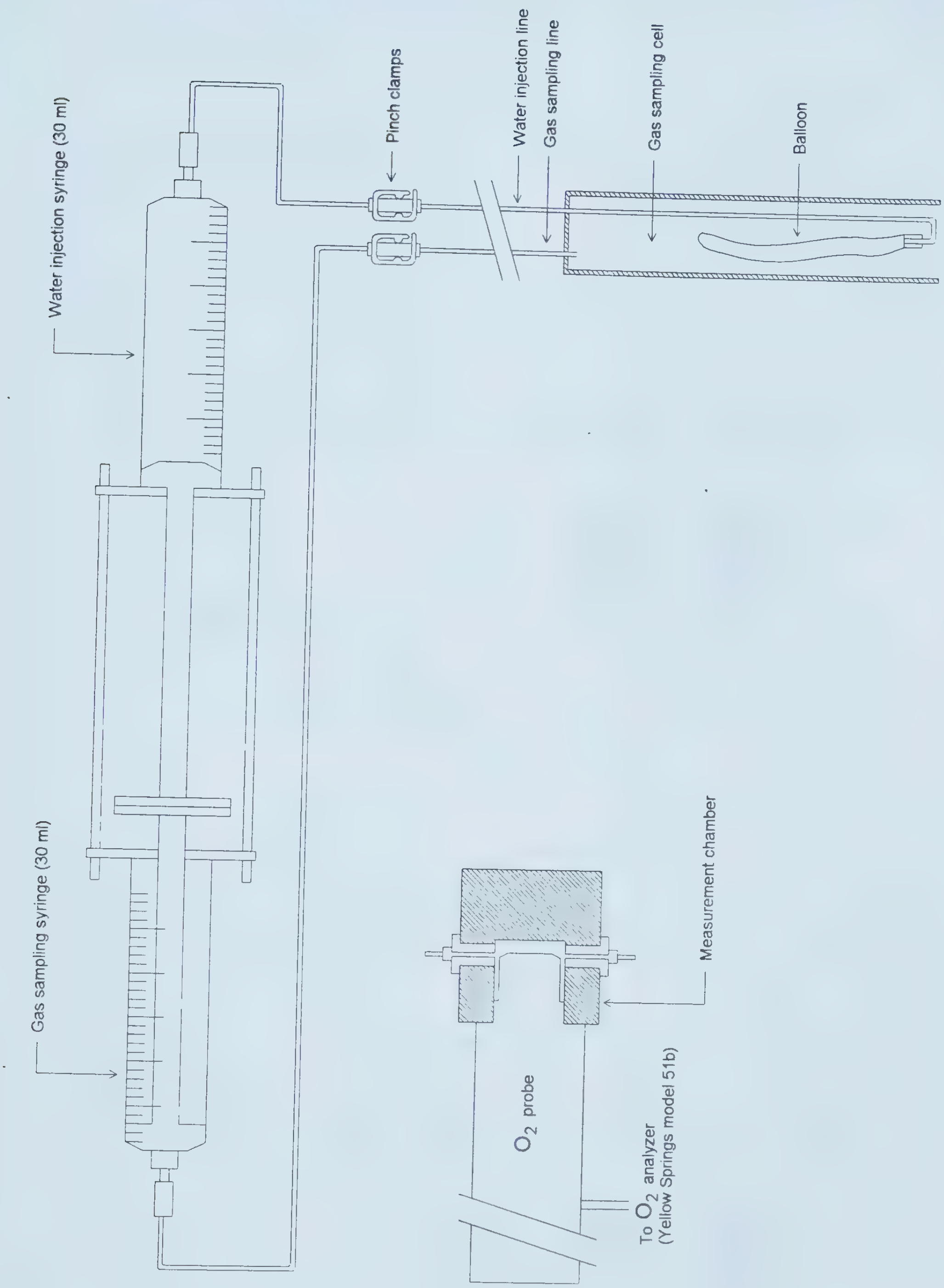


Figure 3-6 Precipitation (right y axis) and water table levels (left y axis) at meteorological stations (a,b,d, and e), and mean seasonal water table levels at sample plots (c and f) in drained and undrained areas of Saulteaux River and Wolf Creek. Error bars indicate one standard error of the mean.

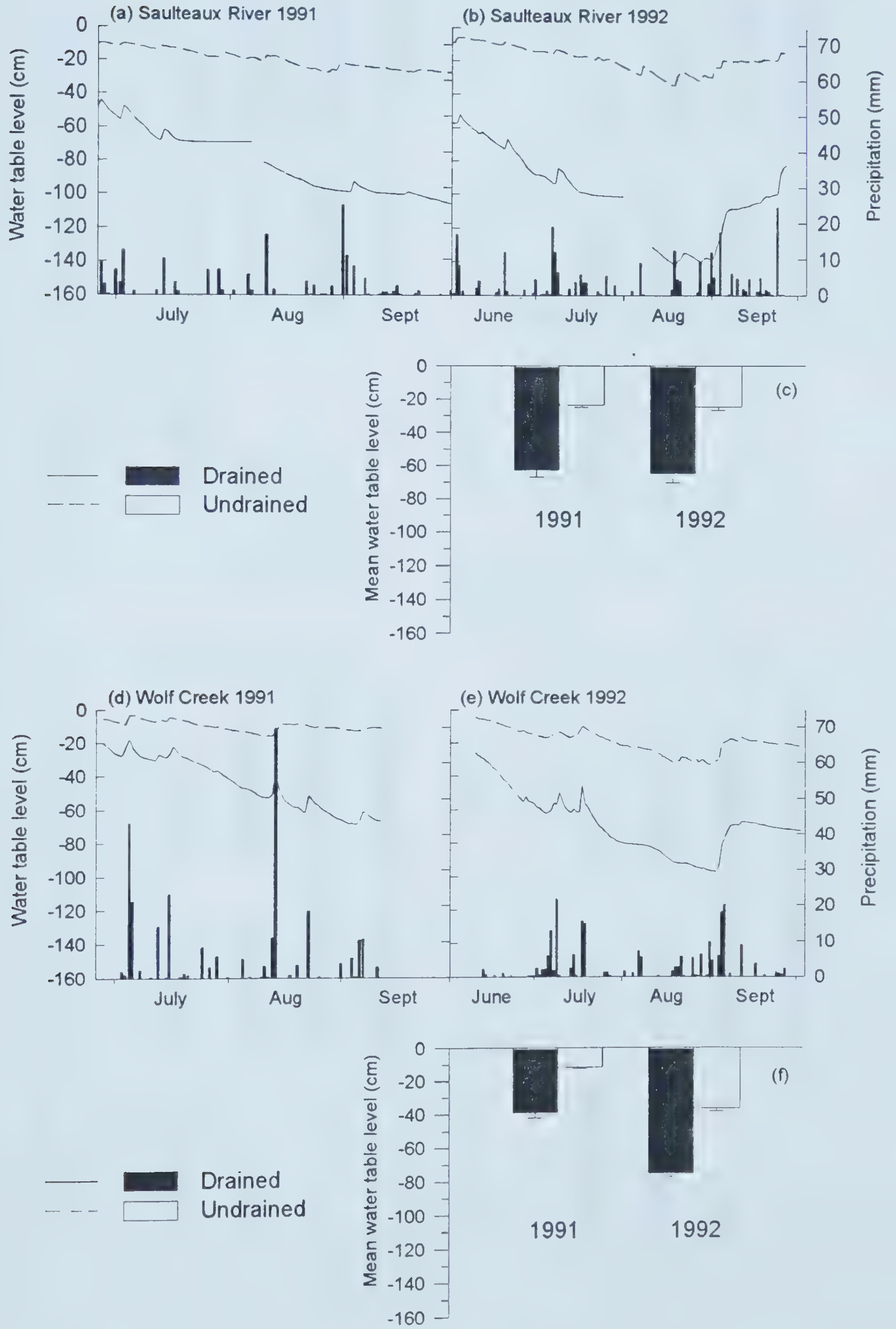


Figure 3-7 Mean soil water content, bulk density, and air-filled porosity for four depth increments in drained and undrained areas at Saulteaux River and Wolf Creek during 1991 and 1992. Error bars indicate one standard error of the mean.

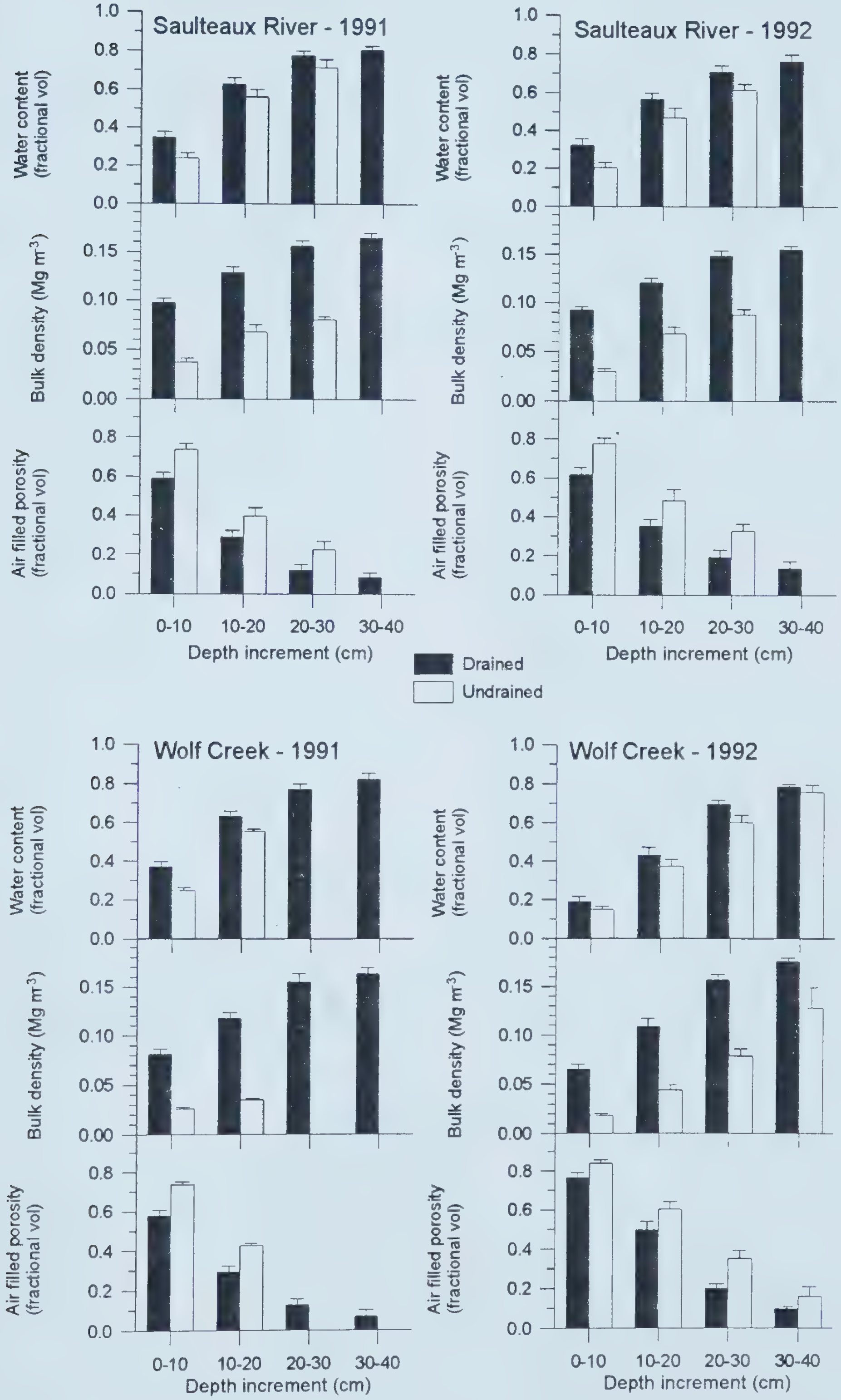


Figure 3-8 Air filled porosity as a function of distance above the water table in drained and undrained areas of Saulteaux River and Wolf Creek during 1991 and 1992. Lines indicate relationships described using the function; $y=a+bx^c$ (solid=drained, dashed=undrained).

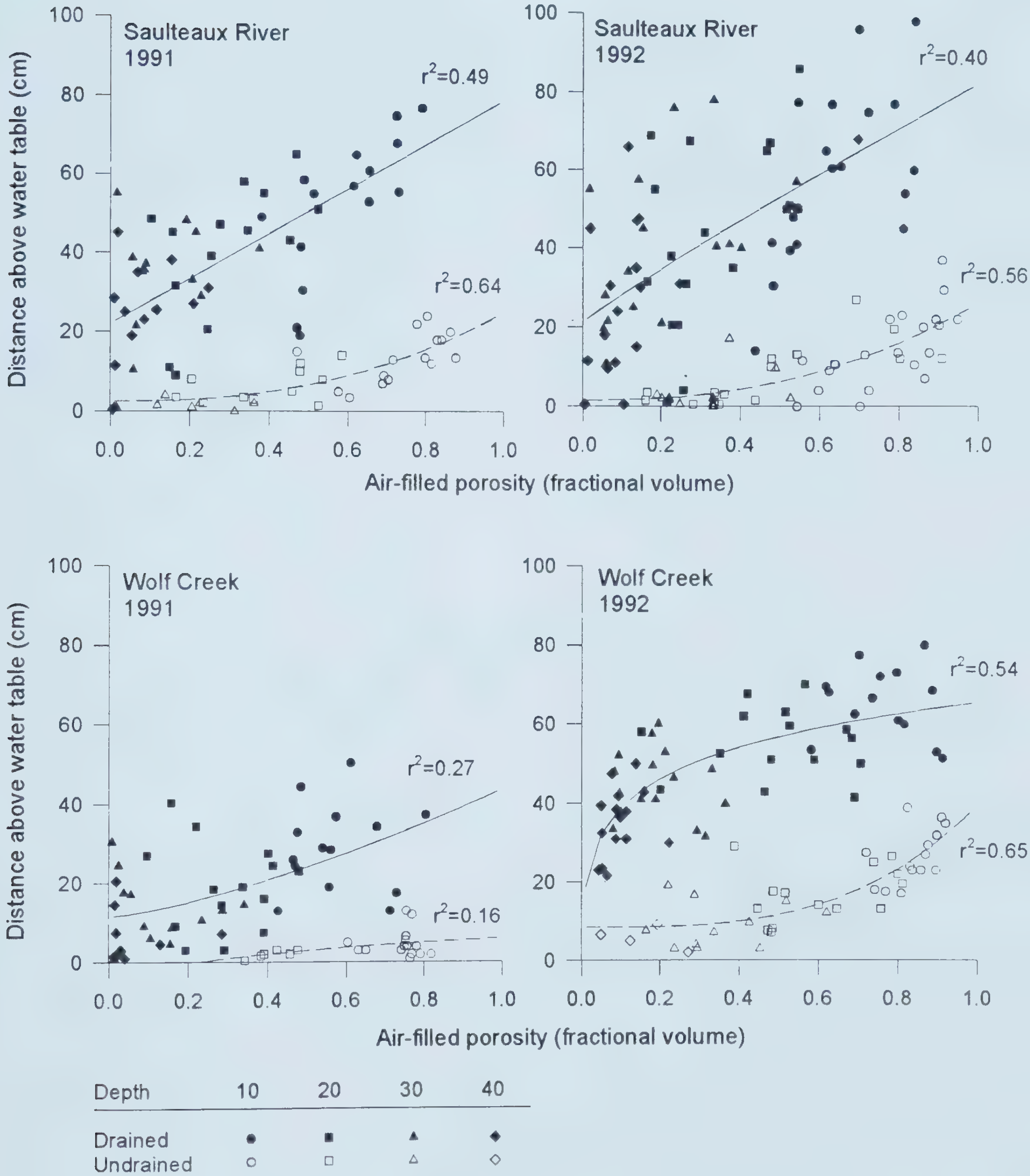


Figure 3-9 Mean seasonal soil oxygen flux measured with "Raney" probe at four depths in drained and undrained areas of Saulteaux River and Wolf Creek during 1991 and 1992. Error bars indicate one standard error of the mean.

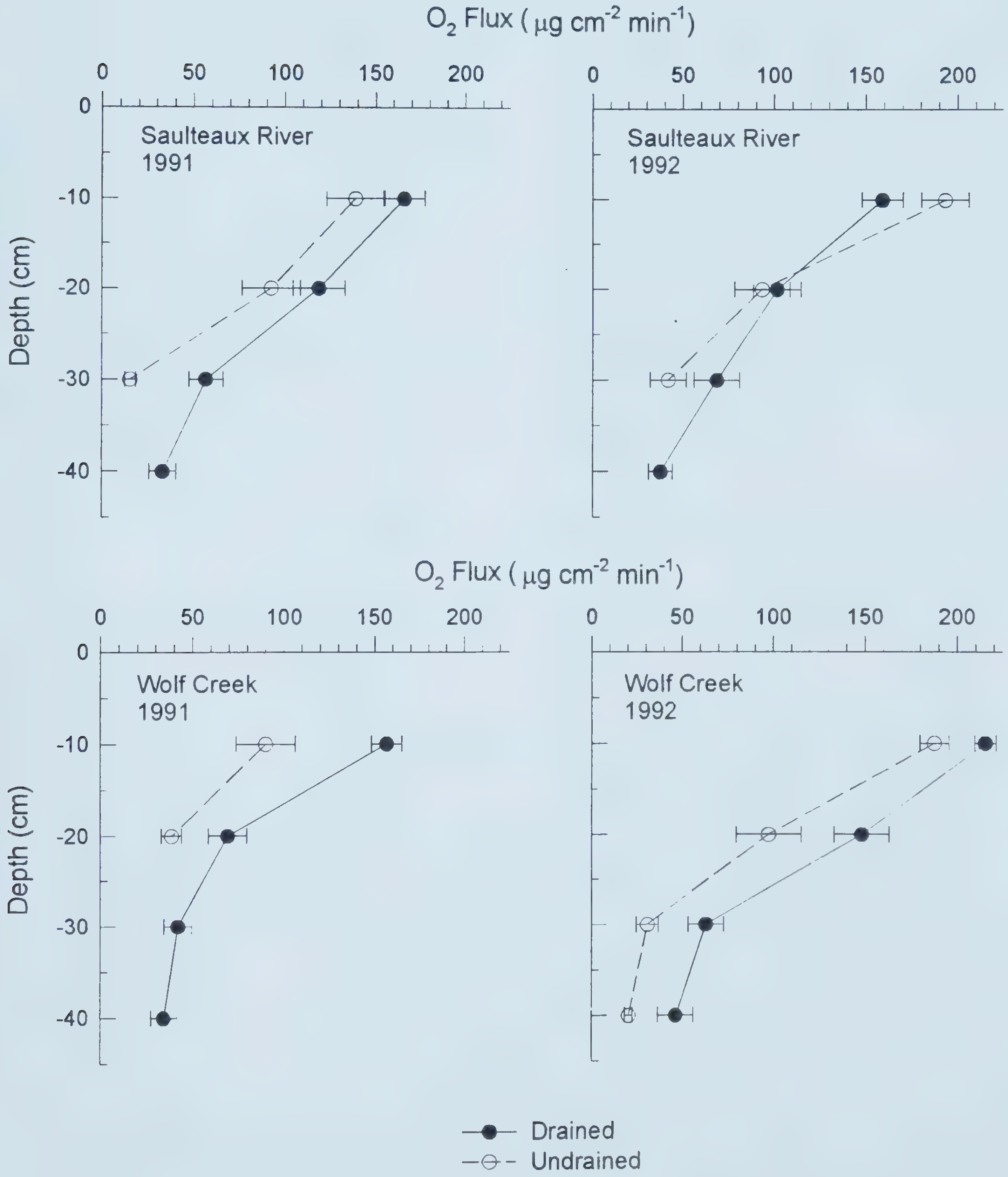


Figure 3-10 Soil oxygen flux measured with "Raney" probe as a function of distance above the water table in drained and undrained areas of Saulteaux River and Wolf Creek during 1991 and 1992. Lines indicate linear relationships (solid=drained, dashed=undrained). Horizontal line indicates water table level.

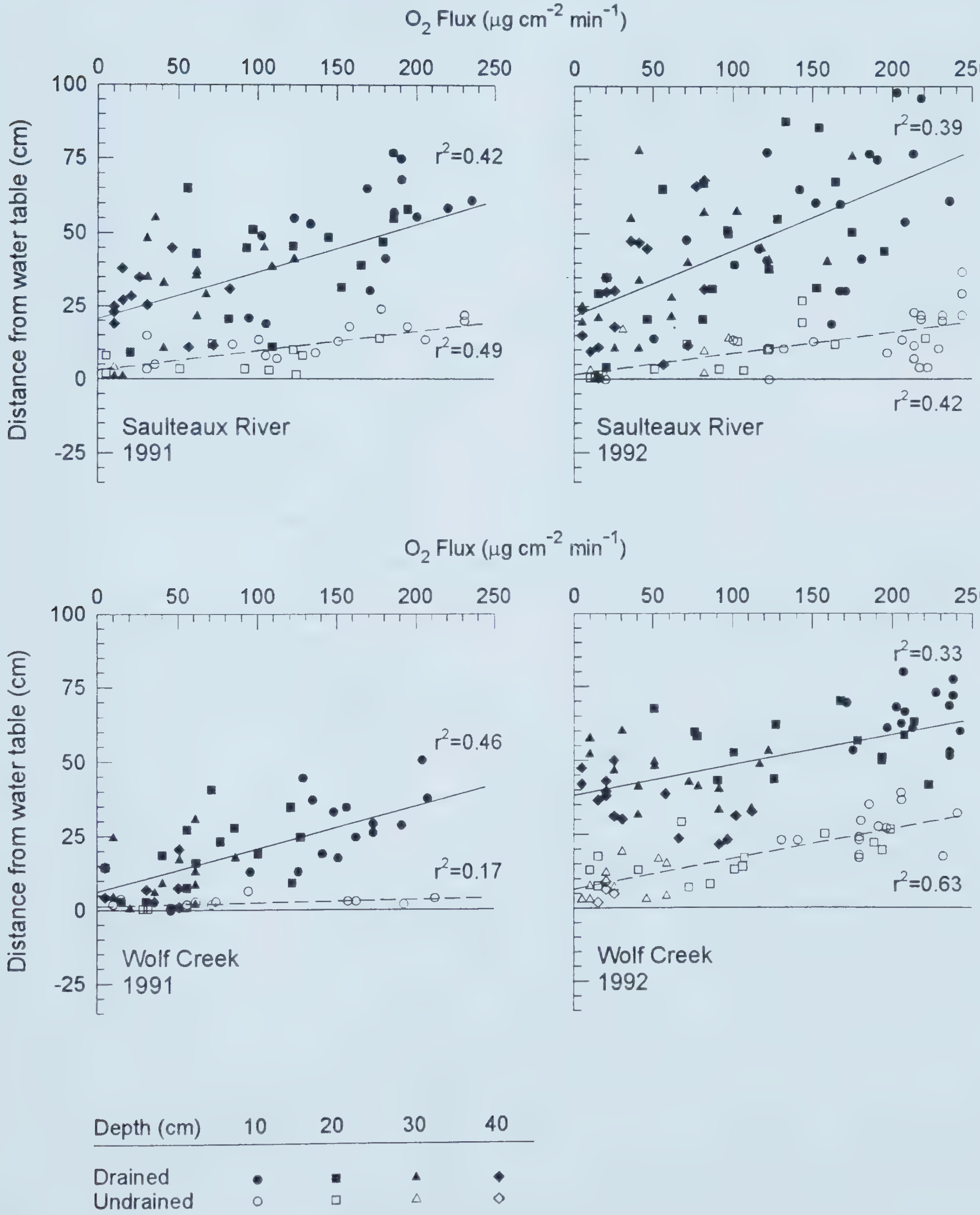


Figure 3-11 Relative oxygen diffusivity as a function of air-filled porosity in drained and undrained areas at Saulteaux River and Wolf Creek. Includes data from both 1991 and 1992. Lines indicate the form of non-linear relationships (solid=drained, dashed=undrained).

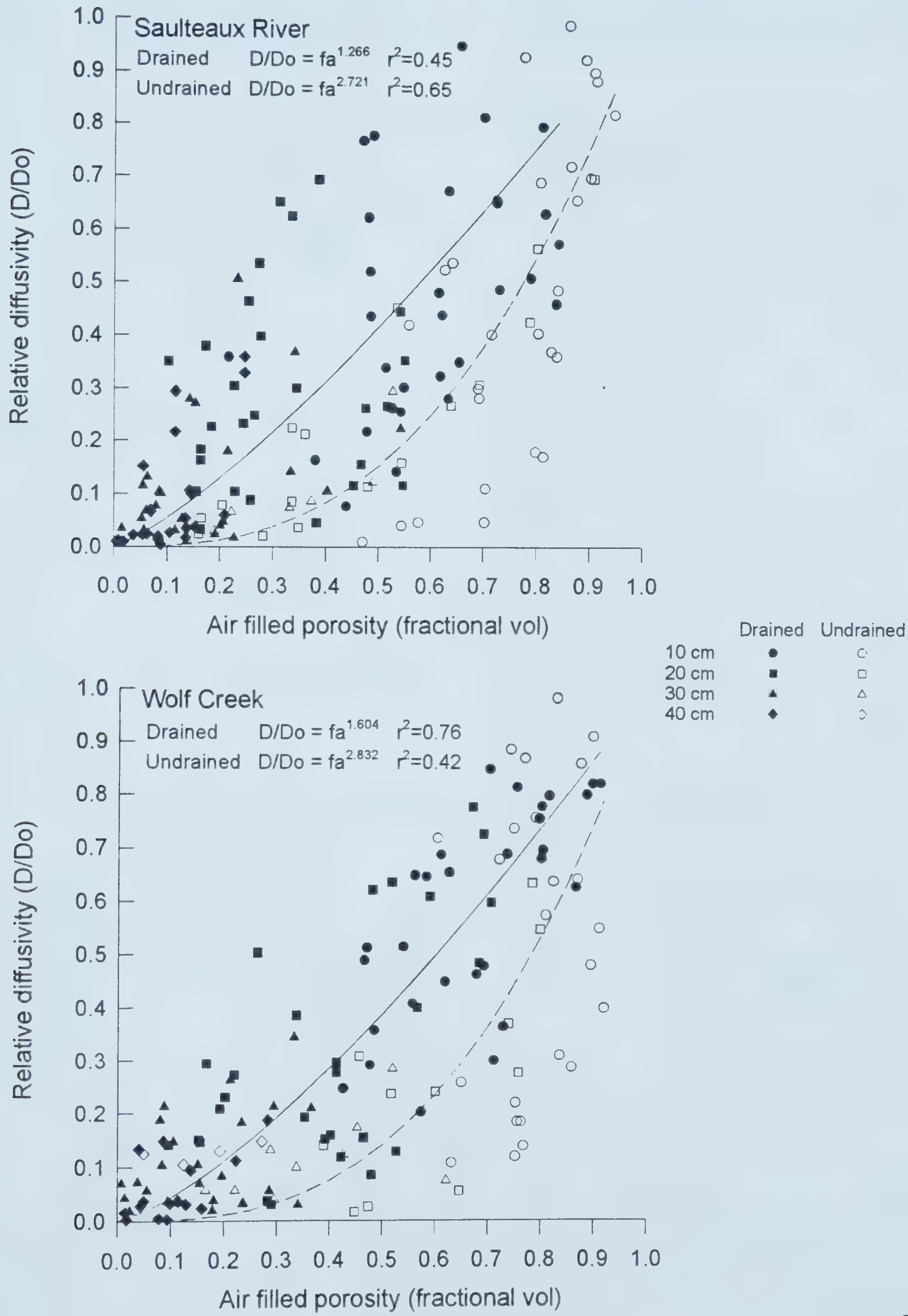


Figure 3-12 Mean seasonal ODR (oxygen diffusion rate - Pt micro-electrode method) for four depths; and ODR as a function of distance above the water table in drained and undrained areas of Saulteaux River and Wolf Creek during 1992. Error bars indicate one standard error of the mean. Lines on bottom series indicate relationships described using the function; $y=a+(b-a)c^x$ (solid=drained, dashed=undrained, horizontal line indicates water table level).

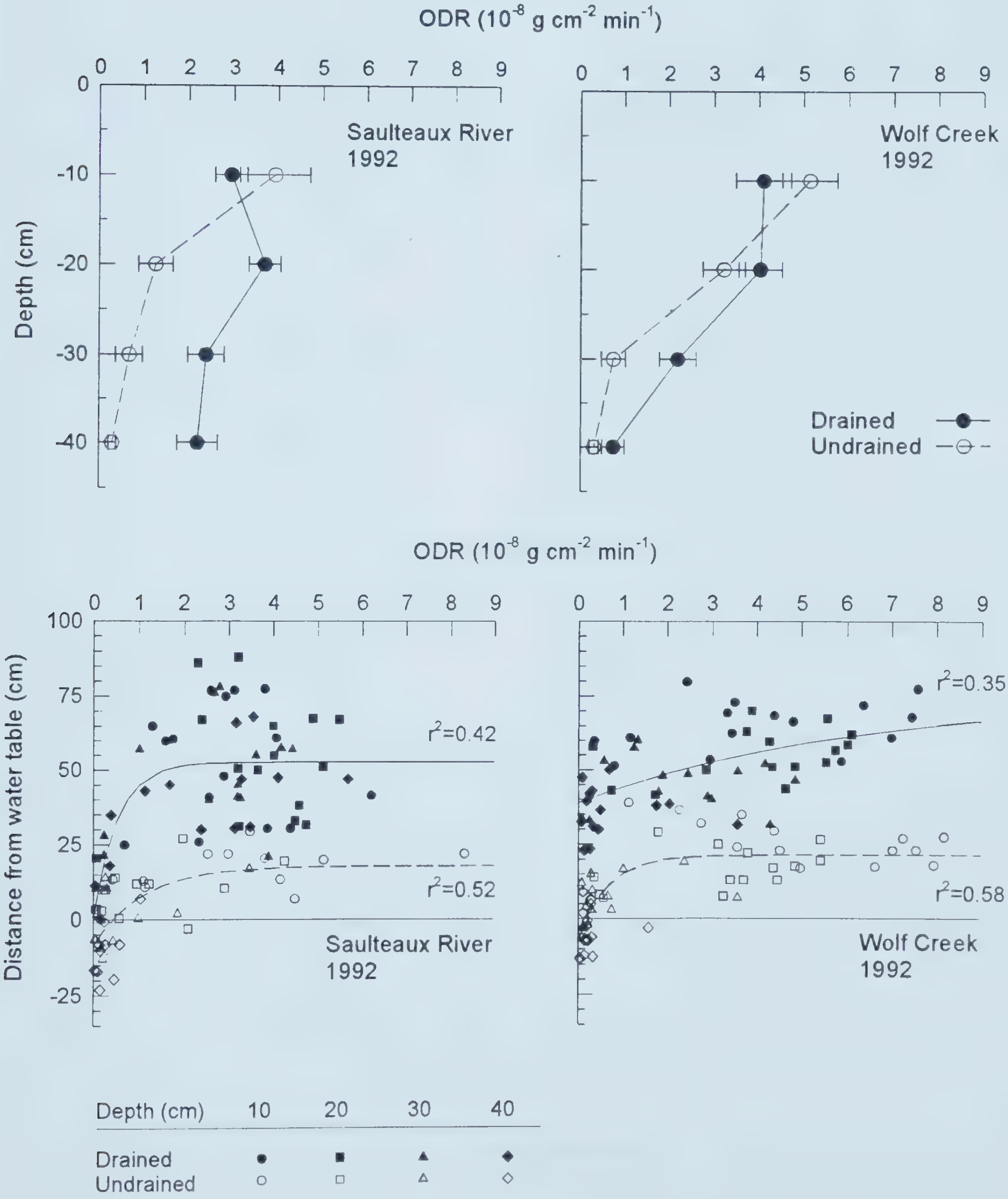


Figure 3-13 Mean seasonal soil oxygen concentration for four depths in drained and undrained areas of Saulteaux River and Wolf Creek during 1991 and 1992. Error bars indicate one standard error of the mean.

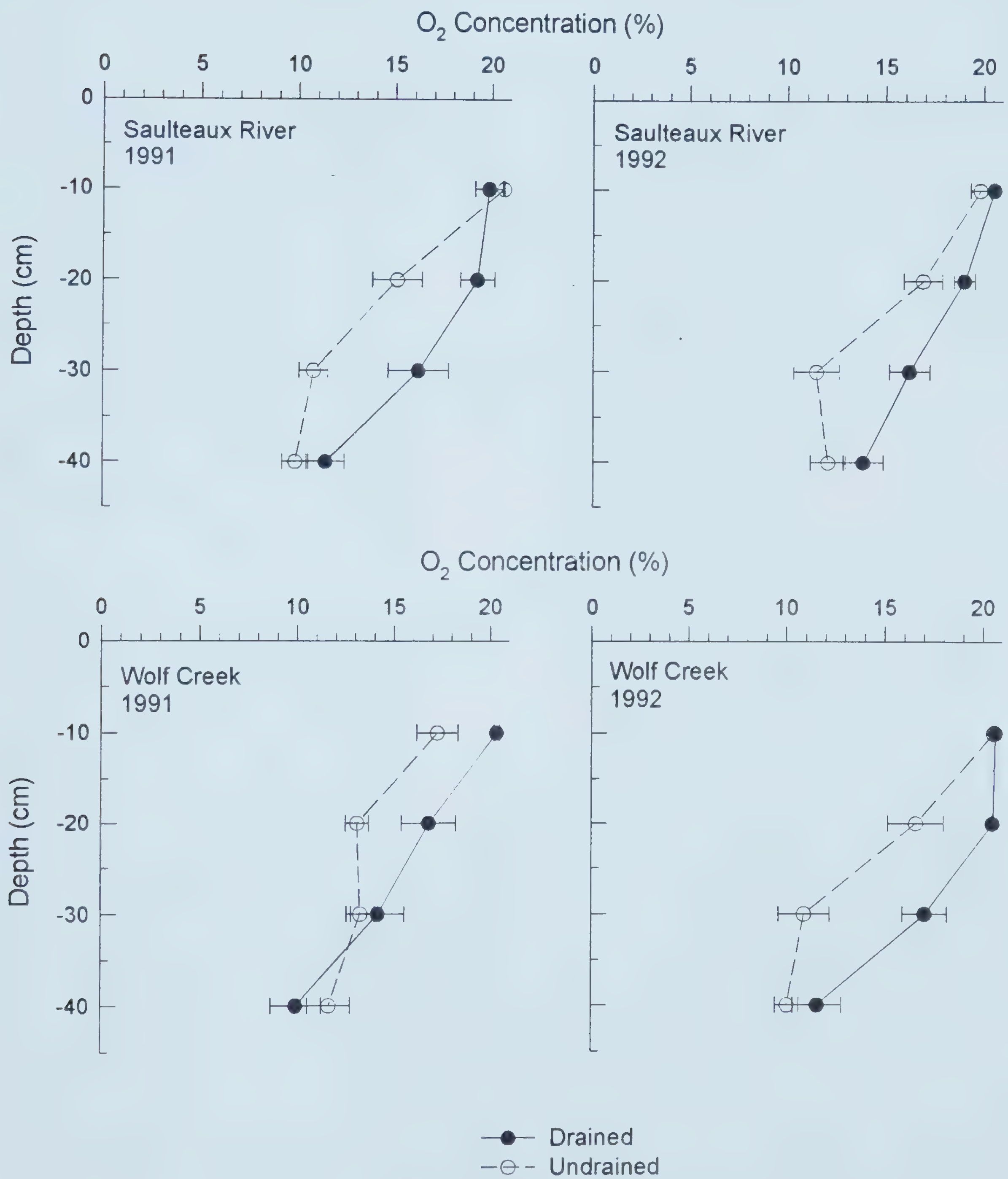


Figure 3-14 Soil oxygen concentration as a function of distance above the water table in drained and undrained areas of Saulteaux River and Wolf Creek during 1991 and 1992. Lines indicate relationships described using the function; y=a+(1/(1+bx)) (solid=drained, dashed=undrained). Horizontal line indicates water table level.

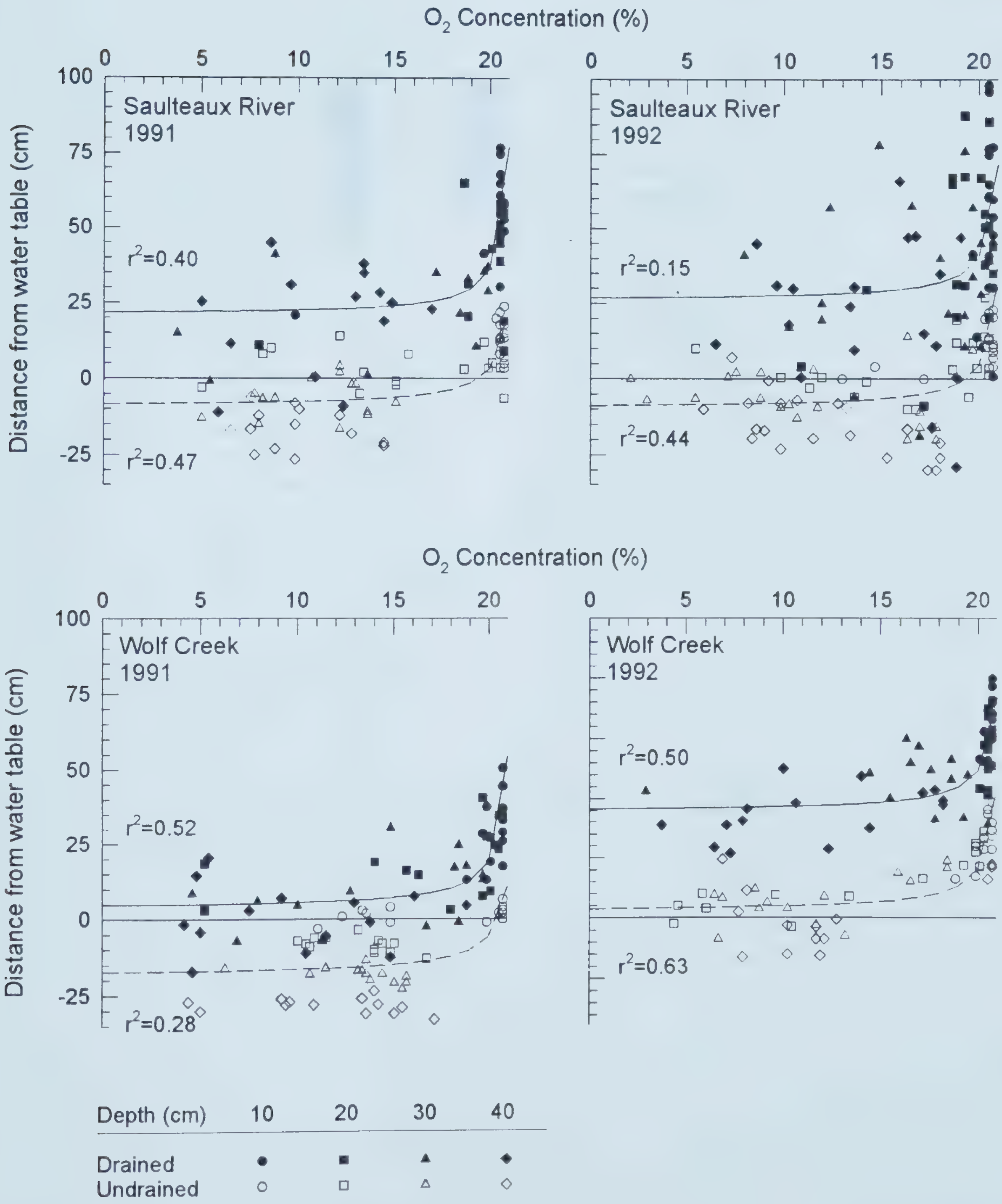


Figure 3-15 (a) Mean aerobic limit (bars) measured by oxidation of steel rods and water table depth (symbols), and b) aerobic limit depth as a function of water table depth in drained and undrained areas of Saulteaux River and Wolf Creek during 1992. Zero on the y axis indicates the peatland surface. Error bars indicate one standard error of the mean. Dashed line indicates a 1:1 relationship between aerobic limit depth and water table depth.

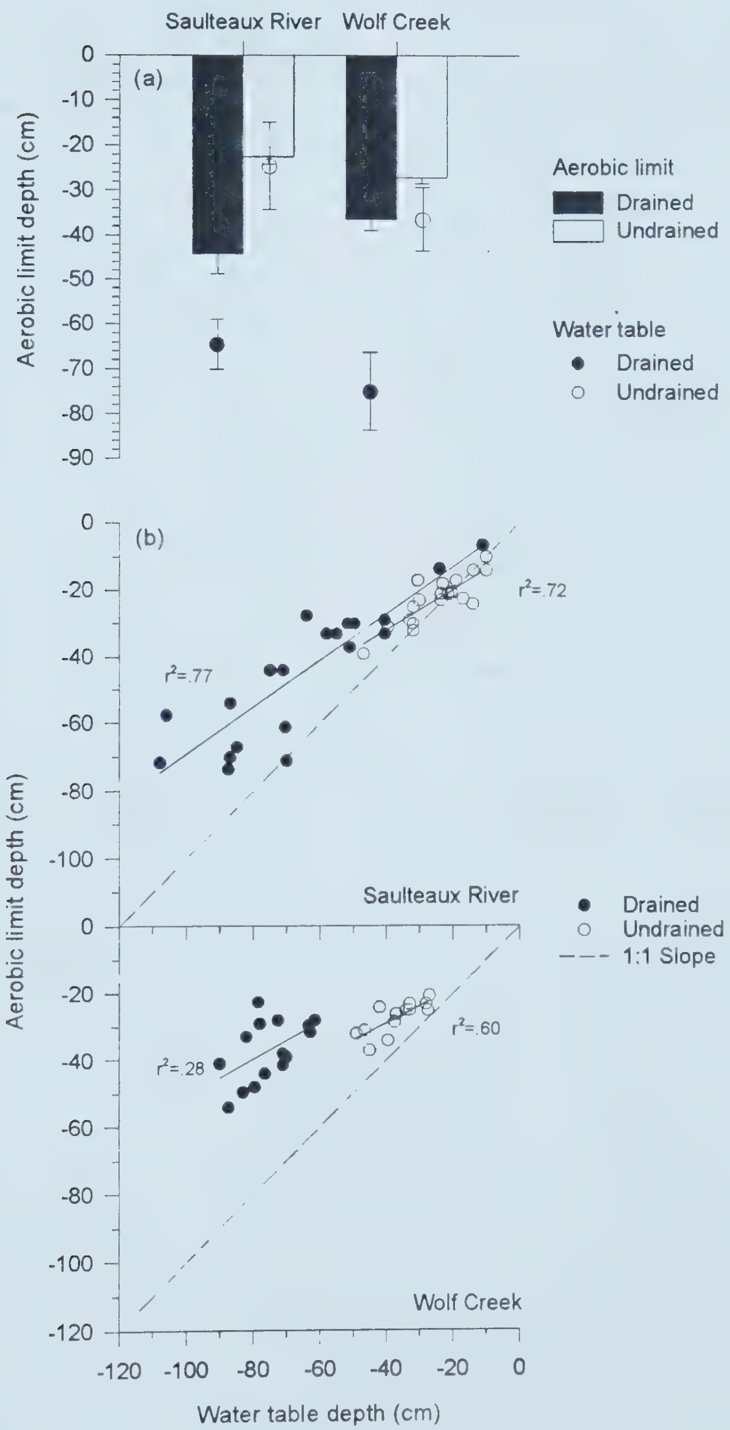
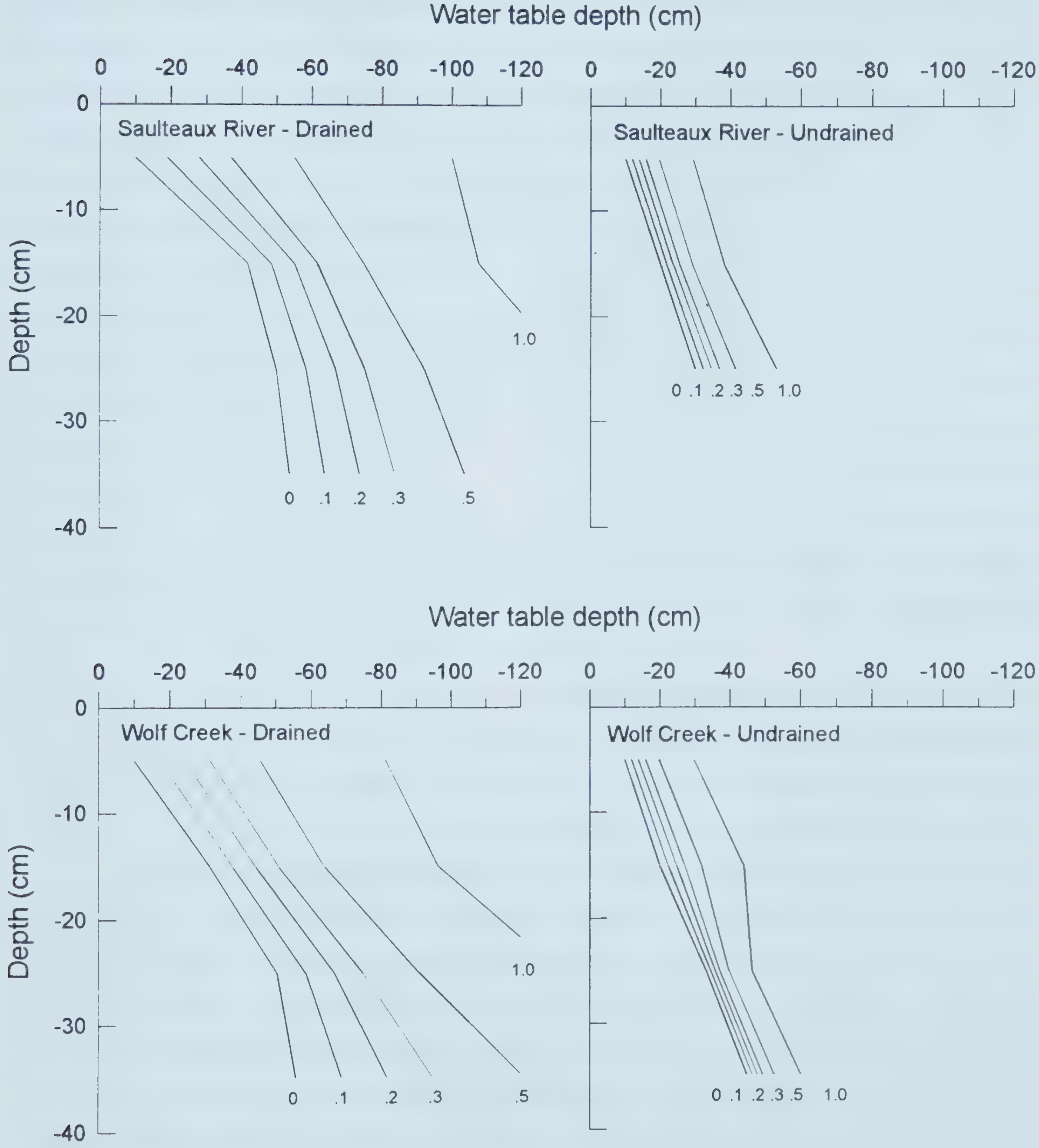


Figure 3-16 Predicted air-filled porosity at four depths as a function of water table depth in drained and undrained areas of Saulteaux River and Wolf Creek. Lines indicate specified air filled pore volumes based on relationships presented in table 3-2.



4 Chapter Four

Spatial patterns of soil oxygen flux (ODR) and aerobic limit depth at two drained and undrained Alberta peatlands.

Water tables can remain near the surface during much of the growing season in many western Canadian fens. As a result, soils in these peatlands are often poorly aerated. The objective of drainage for forestry is to lower, and maintain the water table level below the mean pre-drainage level (Hillman 1992), thereby relieving shallow tree rooting systems from poorly aerated, water saturated soil conditions that restrict tree growth. However, the temporal and spatial effects of forest drainage on soil aeration are not well understood in general, and under Canadian climatic conditions in particular.

Peatland water table levels are temporally dynamic in response to variation in precipitation and evapotranspiration (Boelter and Verry 1977, Ingram 1983). After drainage, water table levels also vary spatially by ditch spacing, and within ditch spacings, between adjacent ditches. The greatest change in water table level occurs within 7-10 m of the ditch edge (Berry and Jeglum 1991, Hillman *et al.* 1990, Rothwell *et al.* 1996). Total water table mounding, the difference in water table levels between ditch edge and the point of greatest elevation between ditches, can vary from 15-45 cm (Berry and Jeglum 1991, Hillman *et al.* 1990, Rothwell *et al.* 1996).

In contrast to time scales of water table variation, soil pore properties are temporally static. However, considerable spatial variation (particularly with depth) exists in many peatlands (Boelter 1964, 1969, Päivänen 1973). Peatland subsidence can also modify the spatial pattern of soil pore properties in as little as 2-3 years after drainage (Rothwell *et al.* 1996). Rothwell *et al.* (1996) report the extent of surface elevation loss and increased peat bulk density (0-30 cm depth) at three drained Alberta peatlands was related to ditch spacing and position relative to ditch edges. Spatial patterns of post-drainage soil water content reflected the interaction of water table levels with altered soil water retention properties associated with subsidence (Rothwell *et al.* 1996). Soil water content (0-30 cm depth) did not differ between ditch spacings despite differences in water table drawdown (Rothwell *et al.* 1996). Within ditch

spacings, water retention in surface peat layers was greatest near ditch edges where water tables were deepest, and subsidence was greatest.

Previous studies have reported that drainage can improve aeration by increasing the air-filled pore space through which oxygen can move into the soil by diffusion from the atmosphere (Boggie 1977, Paavilainen 1967). The temporal response of oxygen diffusion rate (ODR) (Mannerkoski 1985), soil oxygen concentration (Magnusson 1994), and aerobic limit depth (Lähde 1969, 1972, and 1974) to water table fluctuation is well documented in Fennoscandinavian peatlands after forest drainage. However, relatively little has been reported on spatial patterns of aeration after forest drainage. Though variation in mean water table levels at various distances from ditches (Lähde 1969, 1972), and among different ditch depths, and spacings (Lähde 1974) were used to examine temporal variability of aerobic limit depth in Finland, the spatial pattern of post-drainage aeration produced by these factors was not evaluated. As soil aeration can be expected to vary in response to the interaction of spatial gradients in pore properties, with spatial and temporal variation in water table levels, a more complex pattern of post-drainage soil aeration can be expected than if based on variation of mean water table levels alone. Spatial variation in post-drainage water table levels (Hillman *et al.* 1990, Berry and Jeglum 1991) and soil properties affecting water retention (Rothwell *et al* 1996) suggest the pattern of post-drainage aeration will not be easily predicted.

The objective of this study was to describe the spatial variability of soil aeration after drainage of two forested peatlands. Of particular interest was the degree to which post-drainage variation in water table levels, and spatial patterns of subsidence reported by Rothwell *et al.* (1996) were related to variation in soil aeration. As post-drainage subsidence was evident at both peatlands, I hypothesized that the spatial pattern of soil aeration would be inversely related to patterns observed for peat water content by Rothwell *et al.* (1996). Based on observations of greater water retention in drained compared to undrained areas by Rothwell et al. (1996), I expected soil oxygen diffusion rate (ODR) to be lower at similar depths, and aerobic limits to occur shallower in drained compared to undrained areas. Within drained areas, I expected soil oxygen diffusion rate (ODR) to be lower, and aerobic limits to occur at shallower depths in narrower ditch spacings, and near ditch edges where water

table levels are lowest, and subsidence and soil water retention are greatest (Rothwell *et al.* 1996, Lukkala 1949).

4.1 MATERIALS AND METHODS

The study was conducted during the summer of 1992 at two peatlands drained for forestry near Wolf Creek (53°25' N; 116°01' W) and Saulteaux River (55°08' N; 114°15' W) Alberta. Climate, and vegetation at these peatlands is detailed in Chapter's two and three. A 60 ha area at Wolf Creek was drained in 1987 with 30-, 35-, 40-, and 50-m ditch spacings (Hillman *et al.*, 1990). Ditches were 90 cm deep at the time of installation. At Saulteaux River, 50 ha were drained in 1984 with 25- and 40-m ditch spacings with ditches 90 cm deep (Tóth and Gillard, 1988).

The position of the aerobic limit was measured by observing the depth of rust formation on mild steel rods inserted into the peat (Carnell and Anderson 1986). Mild steel welding rods 5 mm diameter and 1.3 m in length were sanded to a bright metal finish before installation. Transects of 8 rods each were established perpendicular to drainage ditches, extending from ditch edges to the mid-point between ditches. Rods were placed at 0, 0.6, 1, 1.8, 3.4, 5.6, 10 m locations from the ditch edge and one at the mid-point between ditches. Rods were inserted into the peat to a depth of 1 m. Six of these transects were established in each of the 30-, 40-, and 50-m ditch spacings at Wolf Creek in June 1992, and in the 25- and 40-m ditch spacings at Saulteaux River in May 1992. Each transect was located in a separate 'ditch to ditch' drainage strips within each ditch spacing. Adjacent undrained areas in both peatlands were used as controls. Undrained transects in both peatlands were located where sub-surface flow was parallel to perimeter ditches (based on topography) to minimize any influence from the drainage area. Six similar transects (each with 8 rods) were established in the undrained area 80 m from perimeter ditches (figure 4-1). Rods were removed after a 4 week incubation period and gently cleaned with a moist cloth to remove adhering soil. Depth from the soil surface to the deepest occurrence of iron oxide was chosen as the position of the aerobic limit (Carnell and Anderson, 1986). Rods were sanded to remove all traces of oxidation/reduction with emery cloth and re-inserted into the soil. Aerobic limit was measured at approximately 30 day intervals (max.=33 d, min.=27 d) from the mid-June through Sept. 1992.

Perforated polyvinyl chloride wells 150 cm long (3.2 cm dia.) were used to measure water table level. Wells were installed into augured holes 130 cm deep at 0, 1, 3.4, and 10 m. from ditch edges, and at the mid-point between ditches. Water table wells were installed in 3 out of 6 transects within each ditch spacing and in the undrained areas. The level of the water table was measured monthly on the same days as the aerobic limit depth.

Soil oxygen diffusion rate (ODR) was measured at -10, -20, -30, and -40 cm from the ground surface using the platinum microelectrode method (Letey and Stolzy 1964). Measurements were conducted once per month (same days as aerobic limit depths and water table levels) in the same transects with water table wells at 0, 3.4, and 10 m from ditch edges within each ditch spacing and in undrained areas. Polarograms (amperage-voltage curves) were generated for each electrode to determine appropriate voltage for ODR measurements (McIntyre 1970). Voltage was applied in 0.1 V increments from 0.1 to 0.9 V. Current was read after 3 minutes. A 2 minute resting period was used before the next voltage increment was applied. Polarograms were similar to those reported in Chapter three. Based on the shape of these curves, a constant applied voltage of 0.4 V was selected for all measurements.

Water table levels, aerobic limit depth, and ODR data were analyzed using a split-plot ANOVA. Ditch spacing, and within-spacing location effects were tested for each site separately using the interaction of the fixed effects with the random effect “transect”. Tests for coincident regressions was performed after Zar (1974).

4.2 RESULTS

4.2.1 Precipitation and water table levels

Precipitation during the summer of 1992 was below normal in central and northern Alberta. Wolf Creek received 244 mm of rain from June through Sept. (approximately 100 mm below long term average for the area), and 257 mm was recorded during the same period at Saulteaux River (50 mm below long term average). Water tables declined steadily after snowmelt from May through August at both peatlands. Water table levels in drained areas were significantly lower than in undrained areas of both peatlands ($p<0.001$). Compared to the undrained portion of the Wolf Creek peatland, drainage

lowered mean water table levels ($p<0.001$) by 53, 42, and 41 cm in the 30-, 40- and 50-m ditch spacings respectively (figure 4-2). At Saulteaux River, drainage lowered mean water levels by 54 cm in the 25-m spacing, and by 59 cm in the 40-m spacing ($p<0.001$). Estimates of mean water table drawdown at Saulteaux River were conservative as the water table was below the bottom of many observation wells by late summer (dry wells were excluded from analysis). During August, water tables in the drained area of Saulteaux River were well below the bottom of the drainage ditches (mean ditch depth was 74 cm in 1992). Differences in water table levels among ditch spacings were not significant at either peatland. Variation in water table levels were observed from ditch edges toward interior positions within ditch spacings at Wolf Creek ($p<0.001$). Differences in water table levels between ditch edge and mid-point positions were least in the 30 m spacing and greatest in the 50 m ditch spacing (figure 4-2). Variation in water table levels within ditch spacings at Saulteaux was less apparent. Though some water table mounding was observed in the 40-m spacing, differences between positions were not significant due to high variability in water table position. No clear water table gradient was observed in the 25-m spacing (figure 4-2).

4.2.2 Aerobic limit depth

Compared to undrained areas, drainage lowered the position of mean seasonal aerobic limits at both peatlands ($p<0.001$). Aerobic limits occurred 60 cm below the surface in the drained portion of the Saulteaux River peatland, and 39 cm below the surface in the drained area of Wolf Creek, which was 38 cm and 11 cm deeper than in their respective undrained areas (table 4-1). Variation in aerobic limit depth roughly paralleled changes in water table levels in drained and undrained portions of both peatlands (figure 4-3). This relationship was more variable in drained areas of both peatlands where water tables were deeper.

Differences in aerobic limit depth among ditch spacings were observed at Wolf Creek ($p=0.010$), though mean aerobic limit depth was not strongly associated with mean water table levels among ditch spacings. Differences in aerobic limit depth between ditch spacings was not significant ($p=0.321$) at Saulteaux River. Similarly, differences in aerobic limit depth by location relative to ditch edges were observed at Wolf Creek ($p=0.010$), while little effect

of location was observed at Saulteaux River (figure 4-4). At Wolf Creek, aerobic limits occurred 6-12 cm deeper near ditch edges than at interior locations. The greatest change in aerobic limit depth occurred within 2-4 m from ditch edges. No clear gradient in aerobic limit depth by location within spacings was observed at Saulteaux River.

4.2.3 Oxygen diffusion rate (ODR)

Oxygen diffusion rate was greater in drained areas of both peatlands compared to their respective undrained areas ($p<0.001$ at Saulteaux River, $p=0.027$ at Wolf Creek). Mean ODR (0-40 cm depth) was 3.18×10^{-8} g cm^{-2} min^{-1} in the drained areas of Saulteaux River, and 2.49×10^{-8} g cm^{-2} min^{-1} at Wolf Creek, compared to 1.65 and 1.73×10^{-8} g cm^{-2} min^{-1} in undrained areas of both peatlands respectively (figure 4-5). Oxygen diffusion rates generally decreased with depth ($p<0.007$). Oxygen diffusion rate varied from 0.02×10^{-8} g cm^{-2} min^{-1} below the water table to 8.20×10^{-8} g cm^{-2} min^{-1} at -10 cm depths in the undrained areas, and from 0.02 to 10.17×10^{-8} g cm^{-2} min^{-1} for similar depths in drained areas. Though ODR profiles were similar within the surface 20 cm, large relative differences between drainage conditions were observed at 30 and 40 cm depths. A drainage by depth interaction ($p<0.001$) was evident at Saulteaux River. Though ODR decreased with depth in the undrained area at Saulteaux River, a similar decrease with depth was not observed in drained areas, perhaps due to very low water table levels in drained areas. A similar interaction between drainage and depth was not observed at Wolf Creek. The generally low oxygen diffusion rates observed at 10 cm depth in drained areas of both peatlands was probably due to poor electrode to soil contact in dry, surface peat.

Though greater mean oxygen flux was observed in drained areas with narrower ditch spacings and/or lower water tables (figure 4-6), differences among ditch spacings were not significant at either site. However, ODR was more sensitive to within-spacing position effects ($p=0.005$ at Saulteaux River, and $p=0.006$ at Wolf Creek) than was aerobic limit depth. At both peatlands, ODR near drainage ditch edges was consistently greater than at interior positions regardless of ditch spacing (figure 4-7). The gradient in oxygen diffusion rate from ditch edge to interior positions was strongest in narrower ditch spacings at Wolf Creek ($p=0.012$, $p=0.028$, and $p=0.18$ for 30-, 40-, and

50-m spacings respectively). No clear difference in the strength of position effects between ditch spacings was apparent at Saulteaux River.

Oxygen diffusion rate profiles above the water table were generally similar in form among peatlands and drainage conditions (figure 4-8). This relationship was described using a 3 parameter empirical model (Ratkowsky 1990); $y=a+(b-a)c^x$, where y and x are the distance above the water table surface, and ODR respectively. Oxygen diffusion rate decreased near the water table in both drainage conditions, though high ODR was maintained closer to the water table in undrained compared to drained areas ($p<0.001$ at Wolf Creek). In undrained areas ODR decreased rapidly when the distance between the measurement point and the water table surface decreased to less than 18.7 cm (horizontal asymptote, parameter a) at Wolf Creek, and 17.0 cm at Saulteaux River. Near zero values were observed 7.0 cm and 11.0 cm below the water table in undrained areas of both peatlands respectively (parameter b). In contrast, a similar rapid decline in ODR was observed in drained areas of Wolf Creek when the distance between the measurement point and the water table surface decreased to less than 59.9 cm, and approached zero when this distance decreased to 37.2 cm. A similar relationship could not be identified in drained areas of Saulteaux River due to persistently low water table levels.

4.3 DISCUSSION

Soil aeration was clearly improved by lowering peatland water tables through drainage. This finding was contrary to my expectations based on increased soil water retention after drainage and subsidence reported by Rothwell *et al.* (1996). Mean oxygen diffusion rates (0-40 cm depth) within drained areas were 1.4-1.9 times that observed at similar depths of undrained areas. Aerobic limits within drained areas were 1.2-2.4 times deeper than in undrained portions of both peatlands. However, greater oxygen transport, and lower aerobic limits in drained areas were associated with much lower mean water table levels than in undrained areas. This result was not surprising given the magnitude of differences in water table levels between drained and undrained areas, and the relationships reported between aerobic limit depth (Bridgham *et al.* 1991, Lähde 1969, 1972, 1974, Mannerkoski 1985), and oxygen diffusion rate (Campbell 1980, Lees 1972, Mannerkoski 1985) with peatland water table depth.

Though spatial patterns of soil aeration were evident, these patterns did not support the hypothesis of decreased aeration at ditch edges and in narrow ditch spacings. These results may have been due to the low water table levels and generally dry conditions during 1992. Consistent with the spatial patterns observed for water table lowering, both ODR, and depth to aerobic limits were generally insensitive to ditch spacing, but were affected by position relative to ditch edges. However, water table variation due to ditch spacing, and within-spacing ditch edge effects was less apparent in the present study than previously observed at these peatlands during years with close to average precipitation (Rothwell and Silins 1990). Brække (1983) also observed greater variation in water table position between ditches during wet years as compared to dry years. Consistent with the findings of Lähde (1969, 1972), soil aeration in the present study (both drained and undrained areas) was more sensitive to water table variation when water tables were closer to the surface. Greater spatial variation in water table position and aeration was observed under the higher water table conditions present in drained areas of Wolf Creek. Thus it may be reasonable to expect stronger post-drainage spatial patterns in water table drawdown and soil aeration during periods of greater precipitation, or early in the growing season when peatland water tables are still high.

However, the results do suggest some reduction of soil aeration at greater depths due to post-drainage subsidence. As the thickness of the capillary zone generally increases when water tables recede into deeper, more humified layers (Päivänen 1973), some deviation of the aerobic limit from the water table surface can be expected (Lähde 1969). However, the magnitude of this deviation was greater in drained than in undrained areas (particularly at Wolf Creek). Larger differences between drainage conditions were evident for ODR profiles above the water table. In undrained areas of both peatlands, ODR decreased rapidly within 18 cm of the water table surface. Though the same general pattern of aeration within drained soil profiles was observed, rapid reduction in ODR occurred 37-60 cm above the water table. This difference cannot be explained solely by differences in mean water table depth between drained and undrained areas. Compared to undrained areas at Wolf Creek, drainage reduced mean water table levels by only 11 cm, yet ODR was reduced to zero approximately 44 cm above that of the undrained area. Though these data support the general hypothesis that increased soil moisture retention

associated with post-drainage subsidence (Rothwell *et al.*. 1996) may decrease soil aeration, this effect was not evident in surface peat. Rather, by increasing the thickness of the capillary zone above the water table, subsidence appeared to restrict aeration response to water table variation in deeper layers. Though surface soils in drained areas of both peatlands were clearly better aerated due to lower water table levels, greater reduction of aeration due to subsidence might be expected during wetter years.

Differences in aeration between drained areas of Saulteaux River and Wolf Creek were associated with differences in water table levels. Despite greater precipitation at Saulteaux River, water table levels within the drained areas were lower than at Wolf Creek. Considerable canopy development of trees, and vigorous growth of understorey shrubs (primarily *Betula* Spp.) occurred at the Saulteaux River site during the 8 growing seasons after drainage (U. Silins - field observations), while a similar growth response was not obvious at Wolf Creek (4 growing seasons since drainage). Increased transpiration and interception losses by trees and shrubs may have augmented water table reduction and soil aeration at the Saulteaux River site. This assertion is supported by the observation during mid-late summer, of water table levels that were well below the bottom of drainage ditches at Saulteaux River while water table levels in the adjacent undrained area remained near the surface. Lower mean water table levels were also observed in the 40-m drained area where average stand density and height of overstorey trees were somewhat greater than in the 25-m area. Several European studies report similar augmentation of drainage effects on water table levels related to tree canopy development. Heikurainen and Päivänen (1970) observed greater interception losses and transpiration in older (>50 yrs.) drained peatlands. Boggie and Miller (1976) suggest increased evapotranspiration coincided with canopy development of *Pinus contorta* 5-6 years after planting and drainage. Compared to unplanted areas, greater air filled porosity (Boggie and Miller 1976) and higher soil oxygen concentration (Boggie 1977) was observed within the rooting zone. Peat water content was reduced to the extent that all but major (perimeter) drains became inactive.

Differences were also observed in aerobic limit depth and oxygen diffusion rate sensitivity to water table variability. In general, ODR was more sensitive to spatial variability in water table level, as reflected in the strength of

ditch spacing and within-spacing position effects. Read *et al.* (1973) and Rayment and Campbell (1980) report ODR was affected by surface micro-topography (ridges and furrows) between adjacent drainage ditches and by position relative to ditch edges. In the present study, ditch edge effects on ODR were evident even where water table variation was weak or absent (i.e. Saulteaux River) suggesting that lateral transport of atmospheric oxygen through drainage ditch walls may be important in the immediate vicinity of drainage ditches. Aerobic limit depth as indicated by oxidation of mild steel rods reflected the position of the oxidizing zone integrated over long periods (i.e. 30 days). Variability in oxidizing conditions during the incubation period may make this technique less sensitive to small differences in aeration than the platinum microelectrode method.

The close association of aerobic limit depth with rapid decline in ODR also supports the conclusions of Carnell and Anderson (1986), and Bridgham *et al.* (1991) who suggest the maximum depth of oxidation on mild steel rods provides an indication of the interface between oxidizing and reducing zones or the top of the capillary fringe in wetland soils. Though the technique has been used to indicate water table position (Hook *et al.* 1987, Bridgham *et al.* 1991) my findings indicated a large difference can exist between maximum depth of rusting and water table depth. The use of steel rods to estimate water table depth may be unsuitable for some soil conditions and should be considered only after careful calibration with water table observation wells.

4.4 CONCLUSION

Drainage was effective in increasing soil aeration in the two forested peatlands studied. Oxygen diffusion rates were greater, and aerobic limits occurred deeper within the drained areas of both peatlands compared to their respective undrained control areas. Though spatial patterns of ODR and aerobic limit depth indicated strong ditch edge effects, little sensitivity of soil aeration to different ditch spacings was evident. This finding was consistent with patterns of water table drawdown observed between different ditch spacings and positions relative to ditch edges within ditch spacings. Water table variation and soil aeration in drained areas were generally greater where water tables were closer to the soil surface suggesting stronger spatial patterns could be expected during average or above average water years or early in the

growing season. Though the low water table depths observed in this study were associated with below average precipitation, the role of increased transpiration and interception losses by trees and shrubs appears potentially important in augmenting drainage effects and modifying water table variability.

Effects of post-drainage peat subsidence were evident at both peatlands as increased distance of both the aerobic limit, and near-zero oxygen diffusion rates from the water table surface. However, reduction of aeration within the rooting zone of peatland trees due to subsidence was not observed due to low water tables within the drained areas of both peatlands.

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Table 4-1 Mean seasonal aerobic limit depth (cm) for undrained, and drained areas with different ditch spacings at Saulteaux River and Wolf Creek. Values in brackets indicate one standard error of the mean.

Saulteaux River		Wolf Creek	
Undrained	25.5 (0.6)	Undrained	28.4 (0.5)
25-m	60.6 (1.6)	30-m	43.0 (1.1)
40-m	59.2 (1.7)	40-m	35.3 (1.0)
		50-m	39.3 (0.9)

Figure 4-1 Drainage design and location of sample plots at Saulteaux River and Wolf Creek.

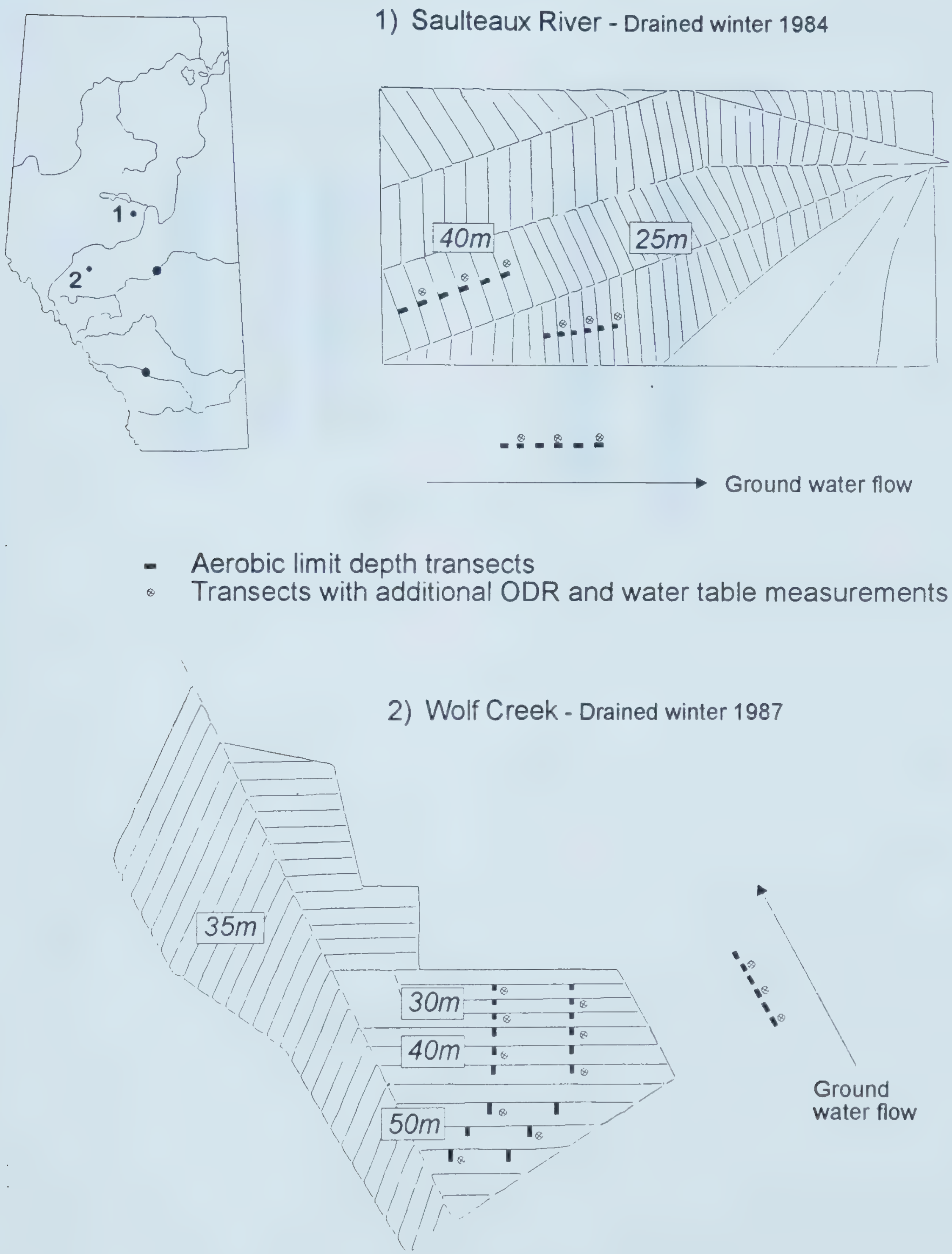


Figure 4-2 (a) Mean summer water table levels (n=45) for undrained, and drained areas with different ditch spacings, and (b) mean cross-sectional water table profiles for drained within-spacing positions by ditch spacing at Wolf Creek and Saulteaux River. Error bars indicate one standard error of the mean.

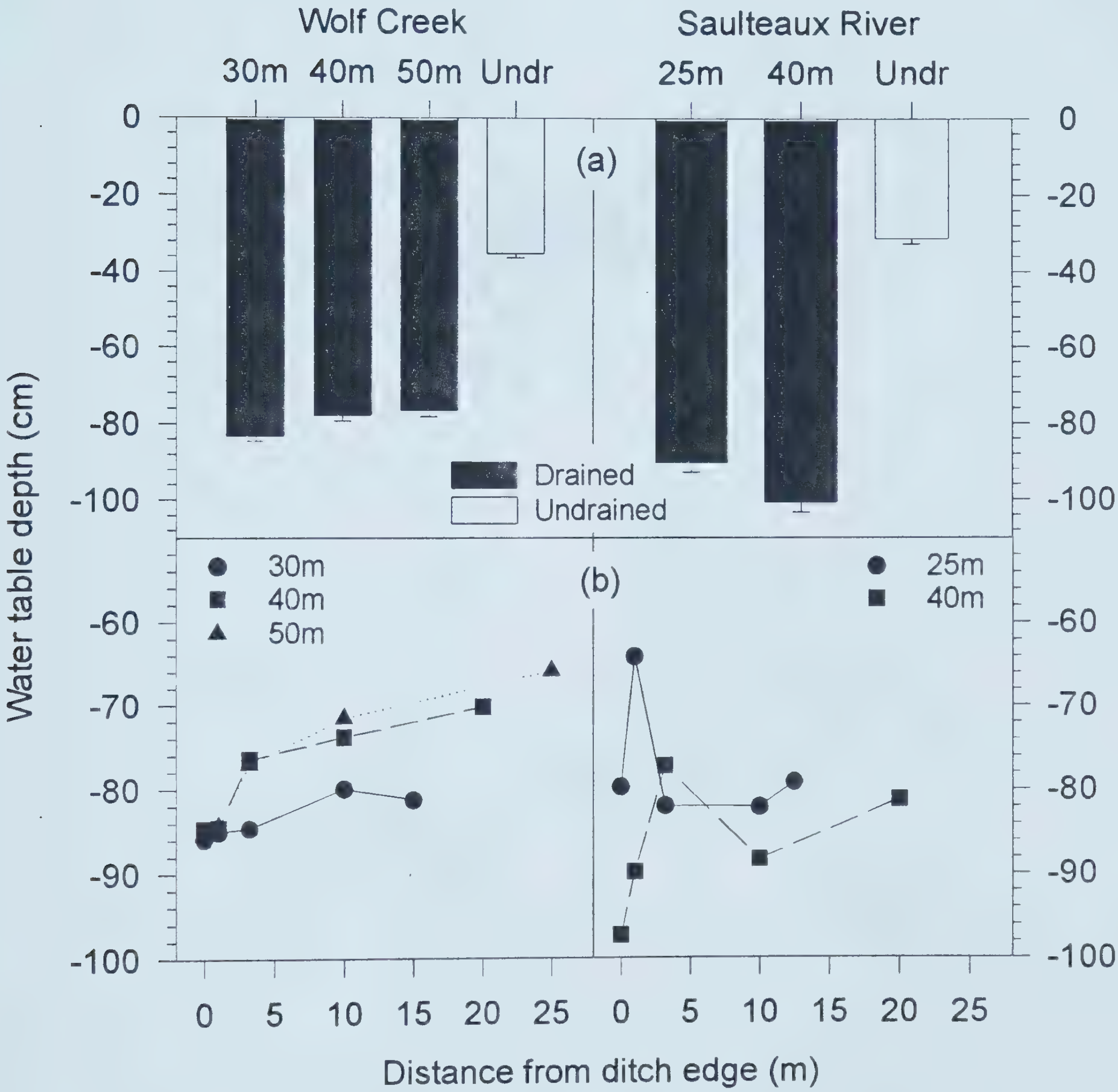


Figure 4-3 Aerobic limit depth as a function of water table level for drained and undrained areas of Wolf Creek and Saulteaux River. Broken line indicates a 1:1 relationship of aerobic limit with water table level. P<0.001 for linear relationships (shown by solid lines) for both sites and drainage conditions.

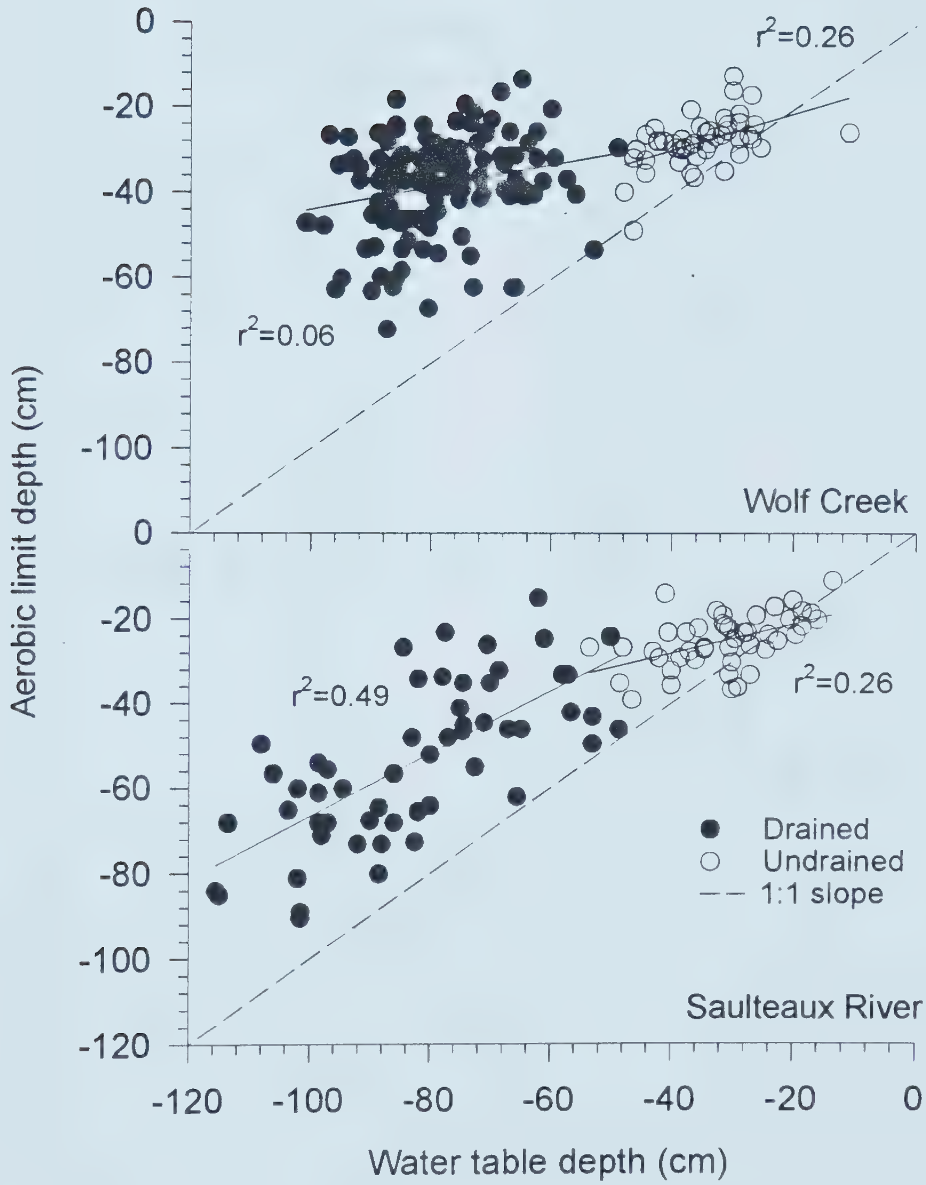


Figure 4-4 Mean summer aerobic limits for within spacing positions in areas drained with different ditch spacings at Wolf Creek and Saulteaux River. Error bars indicate one standard error of the mean.

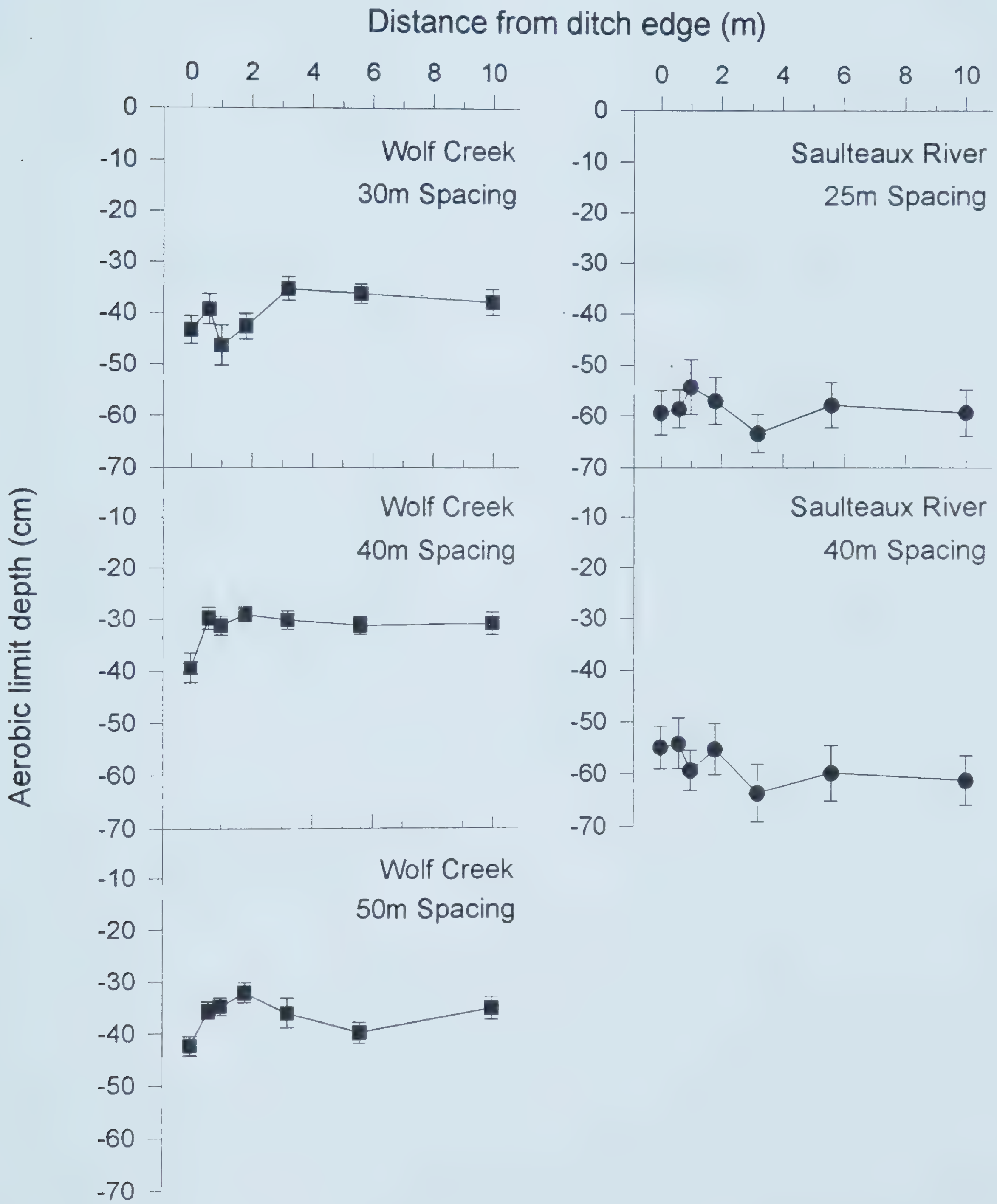


Figure 4-5 Mean summer oxygen diffusion rates (ODR) at four depths for drained and undrained areas (combined data for all ditch spacings and within-spacing positions) at Wolf Creek and Saulteaux River. Error bars indicate one standard error of the mean.

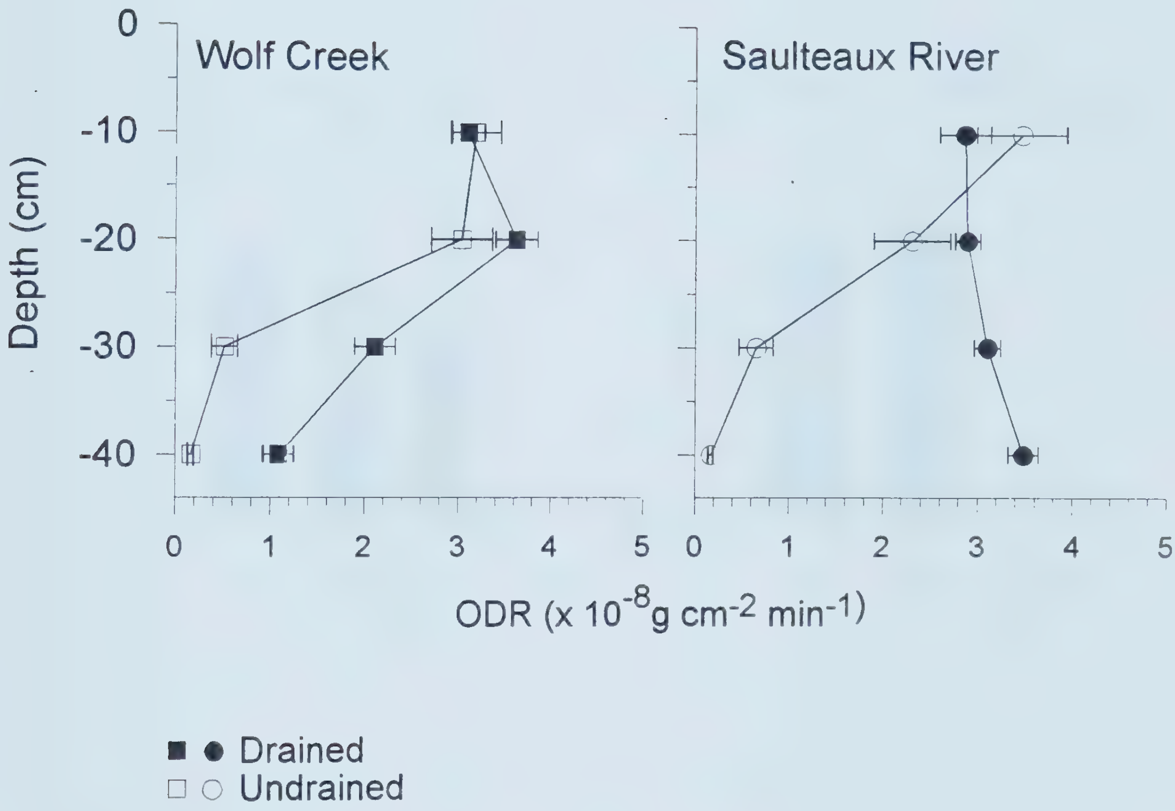


Figure 4-6 Mean summer oxygen diffusion rate (ODR) for undrained and areas drained with different ditch spacings (combined data for all depths and within-spacing positions)at Wolf Creek and Saulteaux River. Error bars indicate one standard error of the mean.

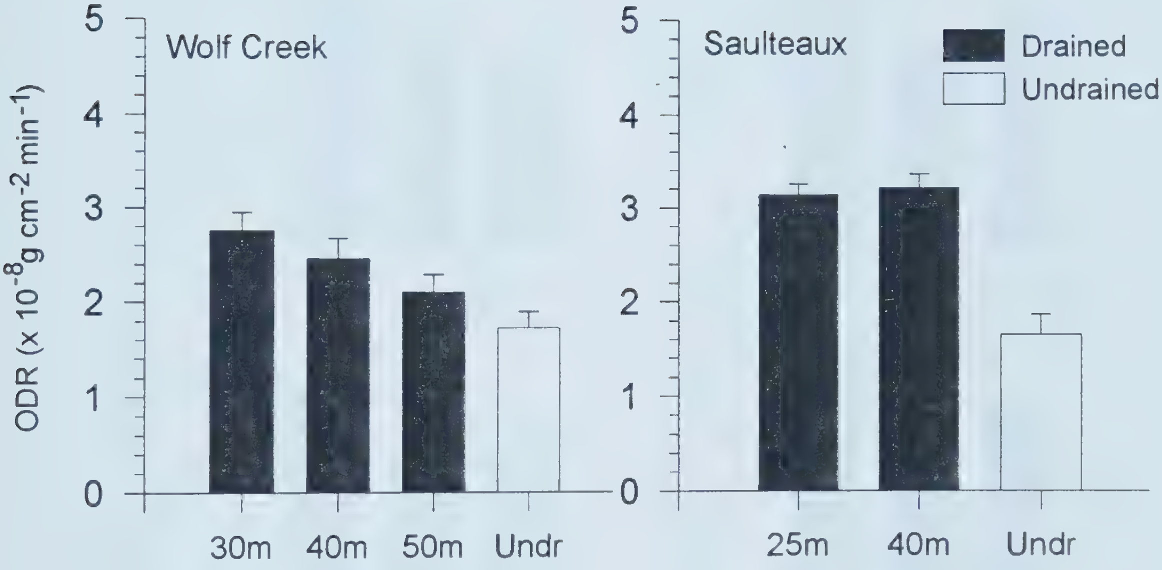


Figure 4-7 Mean (0-40 cm depth) oxygen diffusion rate (ODR) at three within-spacing positions for areas drained with different ditch spacings at Wolf Creek and Saulteaux River. Error bars indicate one standard error of the mean.

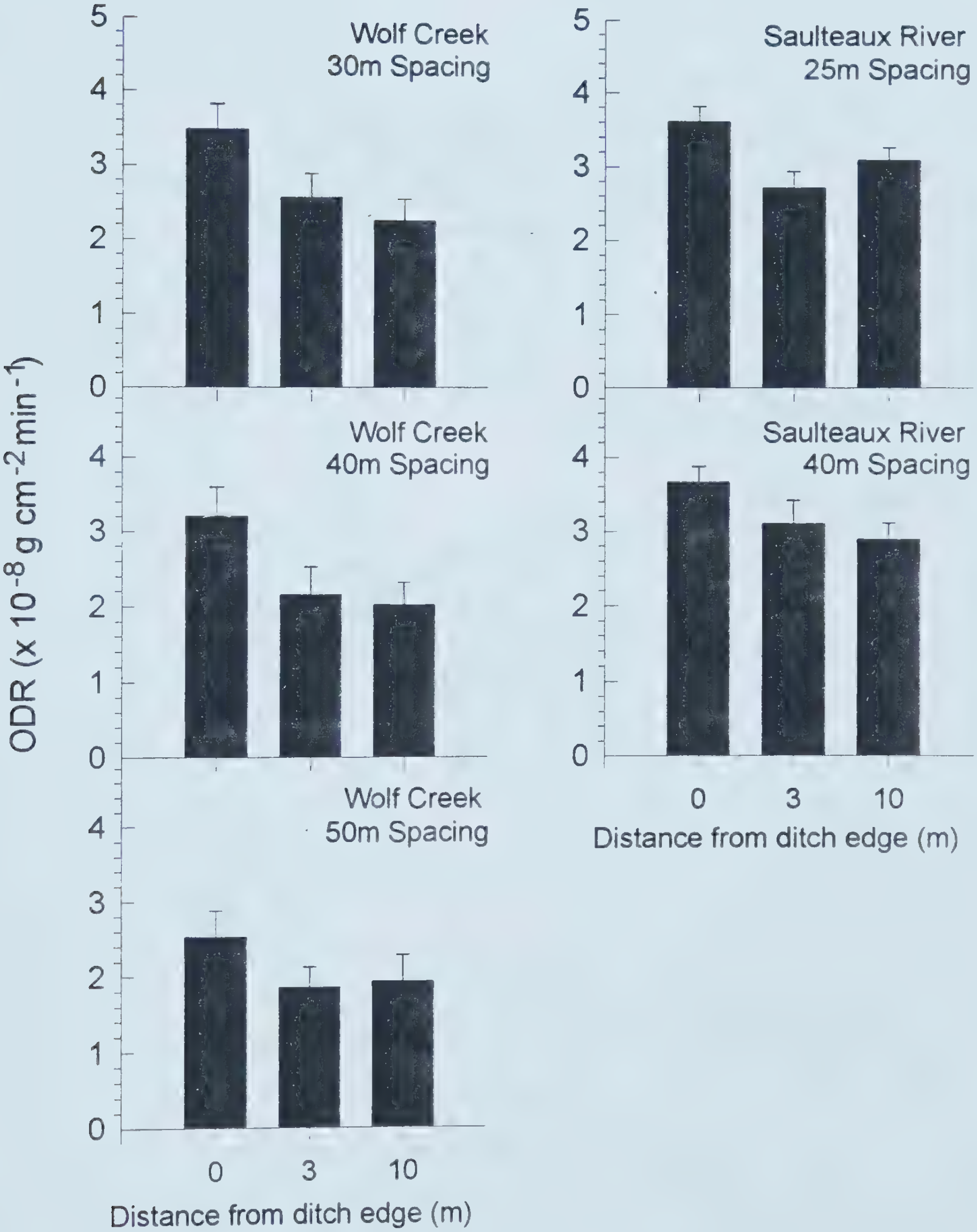
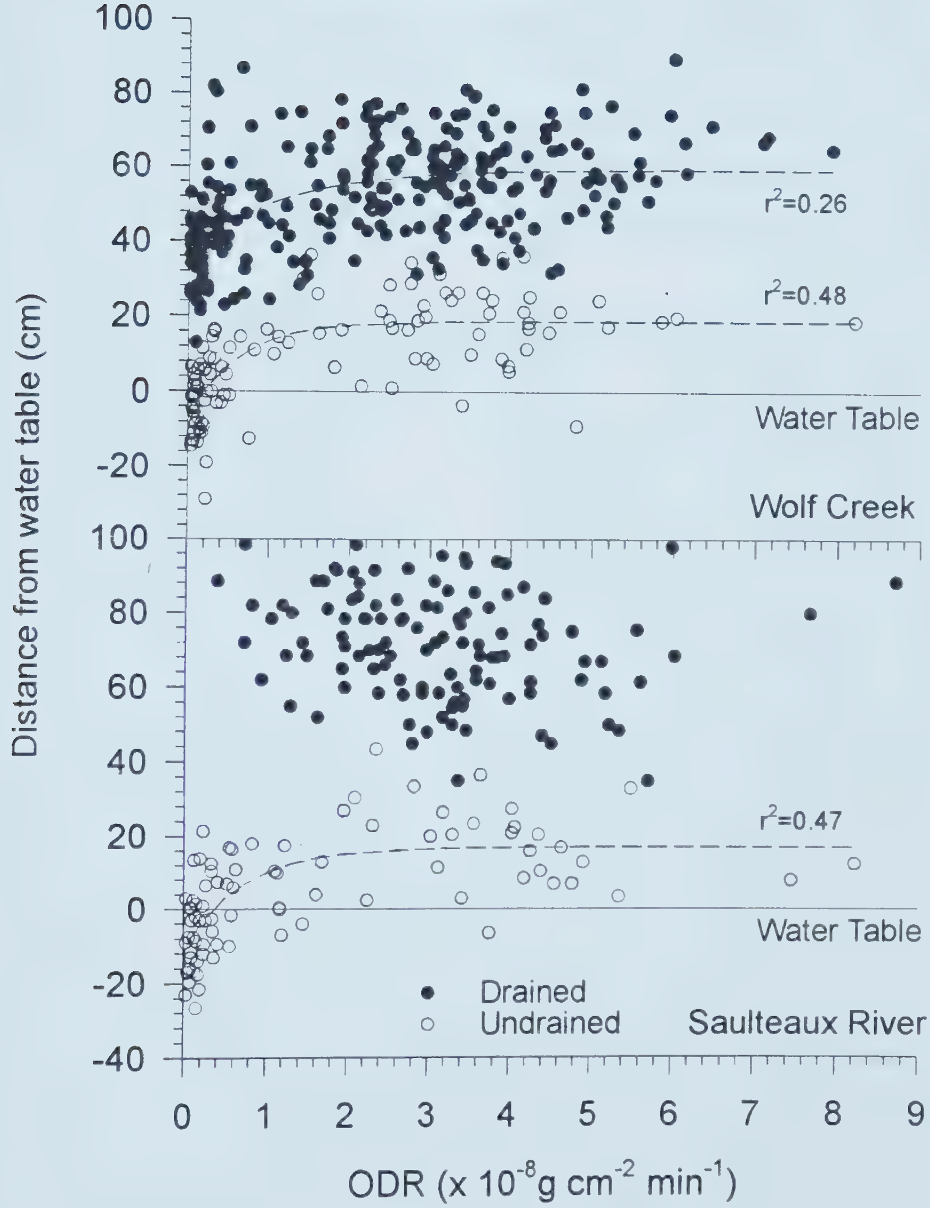


Figure 4-8 Soil oxygen diffusion rate (ODR) as a function of distance from water table for drained and undrained areas of Wolf Creek and Saulteaux River. Dashed lines indicate relationships described using the function; $y=a+(b-a)c^x$ ($p<0.001$). Horizontal line indicates the water table level.



5 Chapter Five

General discussion and conclusions

By altering the surface hydrology of forested peatlands, drainage sets into motion a series of ecological changes that extend beyond simply lowering the water table level. Drainage modifies soil conditions for plant growth, thereby altering the development of trees and other peatland vegetation. These changes can alter the trajectory of peatland forest succession from that of similar undisturbed peatlands (Laine *et al.* 1995). Such transformations involve many abiotic and biotic peatland factors interacting over time, however, it is the lowering of water table level that initiates this series of changes. The present study explored some of the mechanisms involved in the early phases of these transformations.

My results indicated that subsidence directly modified peat hydrologic properties that govern the status and movement of soil water after drainage. However, the extent to which these changes altered soil moisture conditions depended, in part, on variation in water table levels. Thus subsidence effects on aeration can be considered indirect, or interaction effects, as they depend on the degree to which soil moisture conditions are modified. Some probable effects of increased post-drainage vegetation growth (observed, but not measured) on water table, soil moisture and aeration conditions were also observed. Simple hypotheses concerning soil moisture and aeration conditions after drainage and subsidence were based on observed changes to soil pore properties alone, and did not consider these interactions. These observations further illustrate the complex, and dynamic character of peatland response to forest drainage.

My results confirmed that peat pore characteristics were altered by subsidence after drainage. Increased bulk density due to subsidence resulted in a shift of peat pore size distribution towards smaller pore sizes. At Saulteaux River, this shift involved a loss of peat macro-pores (> 600μm dia.) which, when saturated, drain under gravity alone, with a concurrent increase in soil meso-pores (3-30-mm dia.) which drain at water potential between -100 to -300 cm. Increased water retention was approximately proportional to increases in bulk

density, and probably resulted in greater pore tortuosity and/or more occluded or blocked pore pathways in the bulk soil.

Changes to peat pore size distribution had some direct effects on the status and movement of soil water through the soil. In the vadose zone, subsidence increased both the volume of soil water available for plant growth, and the ease with which it can be transported to roots. Mean soil water retention at Saulteaux River was increased by 18% (40 cm depth) to 237% (10 cm depth) over that of undrained areas at water potentials spanning -5 to -15,000 cm head. This corresponded to an approximate 2-3 fold increase of easily available (-25 to -1000 cm head) and decreasingly available (-1000 to -15000 cm head) water for tree growth from 0-40 cm depth. The shift in peat pore size distribution also increased unsaturated hydraulic conductivity of drained peat over that of undrained peat of by 5 times in the easily available water potential range, and by 15 times in the decreasingly available water potential range. Under these conditions trees should be able to maintain high photosynthetic rates without rapid decreases in soil water potential that lead to water stress. However, improvement of peatland tree water relations after drainage in Alberta has not yet been demonstrated. Though some water relations parameters in black spruce and tamarack were weakly affected 5 years after drainage of Saulteaux River, Macdonald and Lieffers (1990) concluded that water relations were not significantly improved by drainage. In a water withholding experiment, I also detected no difference in stem xylem pressure potential of black spruce seedlings grown in peat from drained and undrained areas of Saulteaux River despite differences in soil water potentials between these soils (Rothwell *et al.* 1996). The depth of root penetration was the probable reason for the lack of tree or seedling response to drainage in both experiments. As root systems expand after drainage (Lieffers and Rothwell 1987), the changes to soil water retention and transport characteristics observed in the present research should eventually prove beneficial to water relations of peatland trees.

However, subsidence was also associated with decreased saturated hydraulic conductivity which could negatively affect drainage by restricting saturated flow to drainage ditches (Boelter 1972). Differences in saturated hydraulic conductivity between drained (1.69 cm/h) and undrained areas (14.46 cm/h) were closely associated with differences in bulk density due to

subsidence. Though water table levels in the drained area of Saulteaux River were rarely within the surface 40 cm where decreased saturated hydraulic conductivity was observed, the maximum depth of subsidence effects at both peatlands is unknown. As Finnish research reports increased bulk density to depths of 60-150 cm (Laiho and Laine 1992, Laine *et al.* 1992) 60 years after drainage, some eventual reduction in drainage efficiency due to subsidence is probably a valid expectation.

Effects of post-drainage subsidence on soil moisture conditions related to greater capillary rise were observed in deeper layers. Soil water contents were considerably greater in drained areas of both peatlands despite much lower water table levels compared to undrained areas. Though consistent with laboratory results, the large difference in mean water table levels between drainage conditions makes this result, and those of Rothwell *et al.* (1996), somewhat surprising. In addition, differential pore air/water relationships between drainage conditions were observed above the water table surface. Considered in light of increased post-drainage unsaturated hydraulic conductivity reported in Chapter two, these results strongly suggest that subsidence increased the thickness of the capillary zone above the water table at both peatlands. Based on air-filled porosity profiles, the thickness of the capillary zone varied from 10-30 cm in drained areas, compared to 2-8 cm in undrained areas. This conclusion is consistent with the general understanding of capillary rise phenomenon in peats of differing bulk densities and pore size distributions (Päivänen 1973) however, similar subsidence effects have not, to my knowledge, been previously reported after drainage of forested peatlands.

As expected, greater water retention after drainage and subsidence was associated with lower air filled porosity of peat at both peatlands. However, lower air filled porosity in drained areas (30-200% less than in undrained areas) was not sufficient to cause substantially reduced soil aeration within the surface 40 cm at either peatland. Oxygen transport rates, and soil oxygen concentrations in drained areas were greater, and the level of the aerobic limit was consistently deeper in drained than in undrained areas of both peatlands. This result was unexpected given the relationship of air-filled porosity with gas exchange between the soil and atmosphere (Glinski and Stepniewski 1985). Ten percent air filled pore volume was suggested by Päivänen (1973) as the minimum required for adequate aeration of peatland root systems. Though

subsidence did reduce the water table levels required to maintain this minimum air filled pore space within the top 30 cm of the soil surface, except for brief periods early in spring, water table levels in drained areas were generally well below these minimum levels in drained areas of both peatlands. Though my results for soil oxygen flux and oxygen concentration generally support the 10 % minimum air-filled porosity figure suggested by Päivänen (1973), differences in relative diffusivity as a function of air-filled porosity between drainage conditions indicated that this figure might be modified by the size distribution of air-filled pores.

Many of the subsidence effects on soil aeration observed in this study were related to differences in capillary zone thickness between drainage conditions. By increasing the thickness of the capillary zone, the most notable effect of subsidence on aeration at both peatlands was a restriction of aeration in deeper layers even when the water table declined to very low levels, rather than a restriction of aeration in surface peat layers. In drained areas, oxygen transport rates and O_2 concentrations declined to near-zero values much further above the water table surface than in undrained areas. In Finland, Lähde (1974) observed a similar restriction of aerobic limit depth 7 years after drainage. However, sustained reduction in the depth of aeration due to subsidence over long periods of time is unlikely, or at least, uncertain due to the modifying role of vegetation.

Observation from field studies provided clues to some potential "feed-back" effects of developing vegetation on post-drainage soil moisture and aeration conditions. At Saulteaux River, increased growth of peatland trees (Rothwell and Silins 1990, Yin 1993), and particularly that of bog birch was associated with large increases in total leaf area (U. Silins - field observations), compared to that of adjacent undrained areas. Heikurainen and Päivänen (1970), and Boggie and Miller (1976) suggested greater interception of precipitation and transpiration can be expected after growth release, and particularly after leaf area response of post-drainage vegetation. In the present studies, the recession of water table levels well below the bottom of drainage ditches at Saulteaux River support this supposition. Given deeper post-drainage root penetration (Lieffers and Rothwell 1987), these factors have considerable potential to further alter post-drainage hydrology, and moderate changes to soil conditions caused by subsidence. Increased interception and

water withdrawal by roots could reduce soil water contents and help to maintain sufficient air-filled porosity for aeration within the rooting zone despite changes in pore size distribution, water retention, and capillary rise due to subsidence. These factors probably affected soil moisture and aeration conditions at the peatlands under study, however the magnitude of these effects on the values reported in the present series of studies are highly speculative.

Three general phases of post-drainage peatland transformation in Finland are described by Heikurainen and Pakarinen (1982). Recently drained peatlands lack any obvious vegetation response to drainage, while in the final stage of post-drainage succession, old peatland forests are characterized by a temporally stable vegetation composition resembling that of upland forests developed on mineral soils of similar trophic status (Paavilainen and Päivänen 1995). Transitional peatland forests encompass those in intermediate phases between the former, and latter (Paavilainen and Päivänen 1995). Lower water tables after drainage results in drier conditions that favor the invasion and development of some upland species. However, the present research indicates that post-drainage subsidence can create wetter conditions that could moderate these changes. The hydrologic influence of post-drainage vegetation on these two opposing ecological forces is probably important in determining the trajectory of forest development after drainage. Though differences in vegetation composition among old peatland forests in Finland is associated with time since drainage, nutrient status, and pH, Laine *et al.* (1995) suggests that stable water level control appears to play a major role in determining the type of forest that develops after drainage. By buffering soil moisture and aeration conditions from the "re-wetting" effects of subsidence, rapid vegetation development after drainage may be an important factor in subsequent post-drainage succession. This supposition is supported by Laine *et al.* (1995) who observed greater development of upland vegetation on sites with greater tree volumes, than on sites with volumes less than 50 m^3/ha. The hydrologic effects of greater vegetation development (Heikurainen 1980), in addition to effects on light conditions suggested by Laine *et al.* (1995), were probably involved in these differences.

The results of my research have some implications for operational forest drainage. As subsidence appears to change soil moisture conditions shortly

after drainage, my research supports the suggestion of Rothwell *et al.* (1996) that some of the adverse effects of drainage on peatland thermal regimes suggested by Swanson and Rothwell (1989) may be short lived. Increased soil water contents due to subsidence should increase thermal conductivity, and reduce the excessive insulating effect of dry surface peat reported by Swanson and Rothwell (1989). In a similar context, "over-effective" water table lowering immediately after drainage (Hillman 1992) may be of limited importance to soil conditions over longer periods of time.

My results also lend support to suggestions that the importance of ditch spacing on regulation of post-drainage soil conditions may be somewhat over-stated (Heikurainen 1980). I observed only a weak effect of spacing on soil oxygen transport, and no effect of spacing on the depth of the aerobic limit at Saulteaux River and Wolf Creek. This finding is consistent with the observations of Rothwell *et al.* (1996) who also reported no significant effect of spacing on post-drainage soil water contents. If these results prove related to the spatial variability of post-drainage tree growth in Alberta, the economics of forest drainage might be improved with wider ditch spacings than those previously used in forest drainage trials in Alberta.

Changes in soil water transport characteristics observed in these studies may also prove important in the regeneration of peatland forests after harvest. Reduced saturated water flow to ditches associated with decreased saturated hydraulic conductivity might result in more severe "watering up" problems in peatland sites after clear-cut harvesting. This could result in some regeneration problems associated with excessively wet post-harvest soil conditions on these sites. If control of post-harvest "watering up" by existing drainage ditches is ineffective, improvement drainage or partial-cut harvest systems might be needed to provide additional water level control (Heikurainen and Päivänen 1970) during the regeneration phase in these sites.

My research also indicates the need for additional research in a number of areas. Recent Finnish research into forest drainage effects on the long term carbon balance of peatlands highlights the importance of climate and peatland trophic status on post-drainage subsidence (Laine *et al.* 1992, 1994). Very little is known about the magnitude and variability of subsidence in Canadian peatlands, and under the continental climatic conditions characteristic of many Canadian peat forming regions. Research in this area is needed. The temporal

dynamics of how drainage and subsidence affect growth limiting conditions (soil moisture, aeration, thermal, and nutrient regimes) over longer periods of time is poorly understood and should also be investigated. The relative importance of these effects on growth of Alberta tree species also remains uncertain. For instance, previous research on post-drainage physiology of black spruce and tamarack in Alberta (Macdonald and Lieffers 1990) was conducted shortly after drainage when subsidence effects on soil conditions (Rothwell and Silins 1990) were considerably weaker than those reported in the present research. A better understanding of how these changes affect water relations and growth of trees after subsidence should be developed. In addition, the feed-back mechanisms of post-drainage vegetation development on these conditions are highly speculative and should be investigated.

An understanding of how forest drainage affects non-commercial peatland plant communities and wildlife in Alberta peatlands is particularly weak. Given current public concern about the environmental impact of forest operations in Alberta, developing this understanding may prove paramount to public acceptance of forest drainage practices in this province.

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6 Chapter Six APPENDICES

6.1 APPENDIX 1

Optimization approach

The MULSTP model of van Dam et al. (1990, 1993) allows for flexibility in how the hydrologic parameters of van Genuchten (1980) are estimated. All hydrologic parameters described by equations [2-3] to [2-5] presented in Chapter two (α, n, K_s, λ, θ_s, and θ_r) can be estimated simultaneously, though optimization of θ_s and θ_r is not generally recommended (van Dam et al. 1994). Furthermore, the model can be fit to cumulative outflow $Q(t_i)$ using equation [2-6] in Chapter two (Eching et al. 1994, Marion et al. 1994), or to both cumulative outflow and water retention data $\theta(h)$ using equation [2-7] in Chapter two (van Dam et al. 1994). If known, $K(h)$ data can be added to the objective function (van Dam et al. 1990) for parameter estimation using measured $Q(t_i)$, $\theta(h)$, and $K(h)$ data.

In the present study, three different optimization approaches were examined; 1) optimization of α, n, K_s , and λ from outflow alone, 2) optimization of K_s and λ as in 1), but using fixed values of α and n determined from independent non-linear regression (equation 2-4 in Chapter 2) using water retention data, and 3) optimization of α, n, K_s , and λ using both outflow and water retention data. Though $Q(t_i)$ and $\theta(h)$ were known, independent measurements of K_s and $K(h)$ were not made, thus model performance was assessed by comparing observed and predicted $Q(t_i)$ and $\theta(h)$. Though the reliability of K_s and $K(h)$ estimates were not directly confirmed with this approach, I assumed that the model which best predicted both water retention and unsaturated flow events also produced the most reasonable estimates of K_s and $K(h)$ for each sample.

Though the final parameter values for α, n, K_s, and λ varied among approaches (Table 6-1 and Table 6-2), relative differences among drainage conditions and depths were generally similar. Though the rate of changes in parameter values due to drainage and depth effects also varied somewhat, the general trends were similar among optimization approaches. Differences existed in the predictive performance of the MULSTP model among optimization

approaches. The first approach (optimization on outflow alone) described cumulative outflow well, but predicted peat water retention poorly (Figure 6-1). The second approach (optimization of K_s and λ on outflow with fixed α and n) described water retention accurately, but predicted cumulative outflow poorly (Figure 6-2). The third approach (optimization of α, n, K_s, and λ using both $Q(t_i)$ and $\theta(h)$ data) accurately described both cumulative outflow and water retention (Figure 6-3). Output from linear regressions performed on observed and predicted outflow and water retention are summarized in Table 6-3. The first two approaches clearly provided the best description of outflow and water retention respectively, but did not describe both outflow and water retention well. The third approach predicted both cumulative outflow and water retention almost as well as the best respective predictions provided by approaches 1 and 2. Based on this analysis, parameter estimates from optimizations using both $Q(t_i)$ and $\theta(h)$ data were selected.

Table 6-1 Mean optimized α and n of drained and undrained peat from Saulteaux River for four depth increments obtained using 3 different optimization approaches. Values in brackets indicate 1 standard error (n=10).

	Depth Increment			
	0-10 cm	10-20 cm	20-30 cm	30-40 cm
α (cm^{-1})				
Approach 1				
Drained	38.11 (25.50)	0.52 (0.42)	0.02 (0.01)	0.02 (0.01)
Undrained	123.26 (37.89)	85.54 (39.91)	1.67 (1.06)	0.60 (0.30)
Approach 2				
Drained	18.80 (9.75)	0.43 (0.21)	0.20 (0.12)	0.09 (0.05)
Undrained	214.03 (65.06)	142.71 (69.33)	1.31 (0.52)	0.48 (0.16)
Approach 3				
Drained	58.68 (30.45)	1.347 (0.69)	0.45 (0.44)	0.03 (0.01)
Undrained	298.86 (59.21)	127.99 (59.92)	4.06 (1.88)	3.17 (2.70)
n				
Approach 1				
Drained	1.474 (0.129)	1.345 (0.069)	1.436 (0.057)	1.440 (0.134)
Undrained	1.509 (0.071)	1.338 (0.026)	1.266 (0.027)	1.288 (0.043)
Approach 2				
Drained	1.292 (0.020)	1.335 (0.028)	1.347 (0.024)	1.374 (0.075)
Undrained	1.305 (0.012)	1.292 (0.011)	1.297 (0.013)	1.265 (0.017)
Approach 3				
Drained	1.212 (0.026)	1.282 (0.041)	1.380 (0.034)	1.480 (0.091)
Undrained	1.329 (0.016)	1.224 (0.011)	1.225 (0.027)	1.288 (0.062)

Table 6-2 Mean optimized *Ks* and λ of drained and undrained peat from Saulteaux River for four depth increments obtained using 3 different optimization approaches. Values in brackets indicate 1 standard error (n=10).

	Depth Increment			
	0-10 cm	10-20 cm	20-30 cm	30-40 cm
K_s (cm/h)				
Approach 1				
Drained	20.18 (14.16)	0.75 (0.23)	0.30 (0.14)	0.36 (0.18)
Undrained	433.13 (134.45)	154.22 (77.97)	2.19 (1.02)	2.81 (1.52)
Approach 2				
Drained	278.65 (145.39)	0.10 (0.06)	0.08 (0.06)	0.03 (0.02)
Undrained	659.64 (44.92)	371.75 (145.41)	0.54 (0.29)	0.29 (0.20)
Approach 3				
Drained	158.37 (77.92)	7.40 (3.37)	5.00 (4.60)	0.19 (0.06)
Undrained	551.38 (137.52)	340.71 (109.38)	15.33 (9.56)	37.16 (35.47)
λ				
Approach 1				
Drained	-4.651 (0.240)	-4.985 (0.008)	-4.980 (0.008)	-4.832 (0.147)
Undrained	-3.504 (0.314)	-4.693 (0.157)	-4.976 (0.018)	-4.234 (0.748)
Approach 2				
Drained	-3.424 (0.343)	-4.255 (0.661)	-4.683 (0.211)	-4.388 (0.611)
Undrained	-4.211 (0.212)	-3.902 (0.534)	-4.897 (0.103)	-4.262 (0.738)
Approach 3				
Drained	-4.999 (0.001)	-4.499 (0.401)	-4.986 (0.007)	-4.996 (0.002)
Undrained	-4.500 (0.264)	-4.984 (0.008)	-4.997 (0.001)	-4.786 (0.189)

Figure 6-1 (a) The relationship between observed cumulative outflow measured from Tempe cells and outflow predicted by MULSTEP, and (b) observed water retention and water retention predicted by MULSTEP using optimization of α, n, K_s, and λ on observed outflow (approach 1).

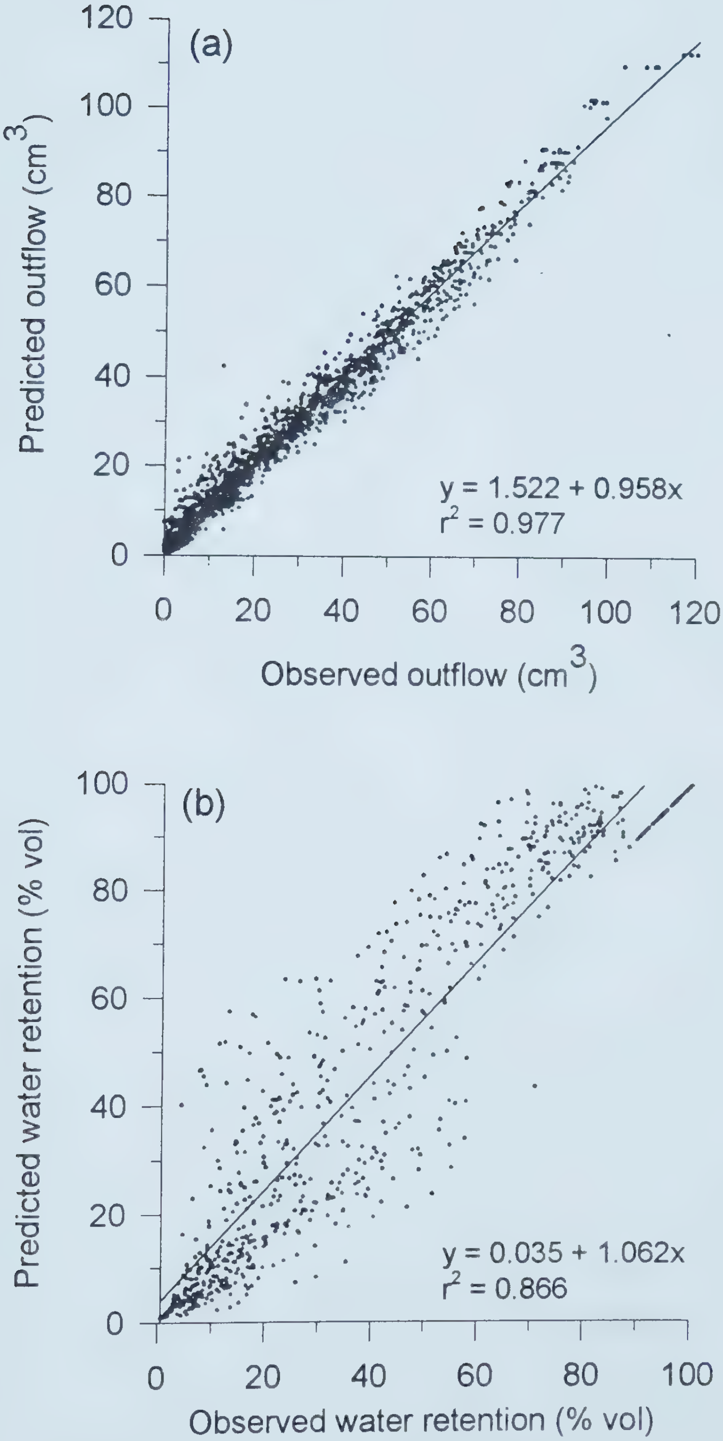

Figure 6-2 (a) The relationship between observed cumulative outflow measured from Tempe cells and outflow predicted by MULSTEP, and (b) observed water retention and water retention predicted by MULSTEP using optimization of K_s and λ on observed outflow with fixed values of α and n (approach 2).

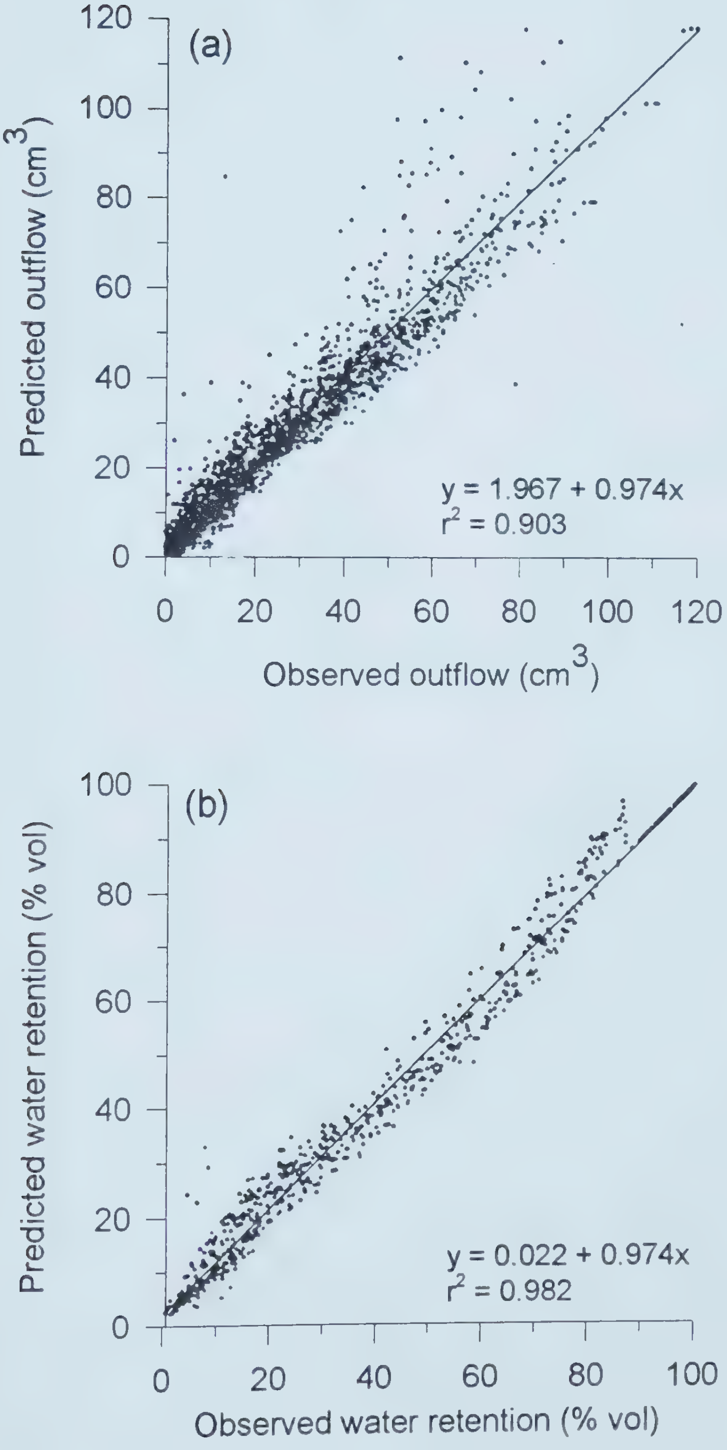

Figure 6-3 (a) The relationship between observed cumulative outflow measured from Tempe cells and outflow predicted by MULSTEP, and (b) observed water retention and water retention predicted by MULSTEP using optimization optimization of α, n, K_s, and λ on both observed outflow and water retention (approach 3).

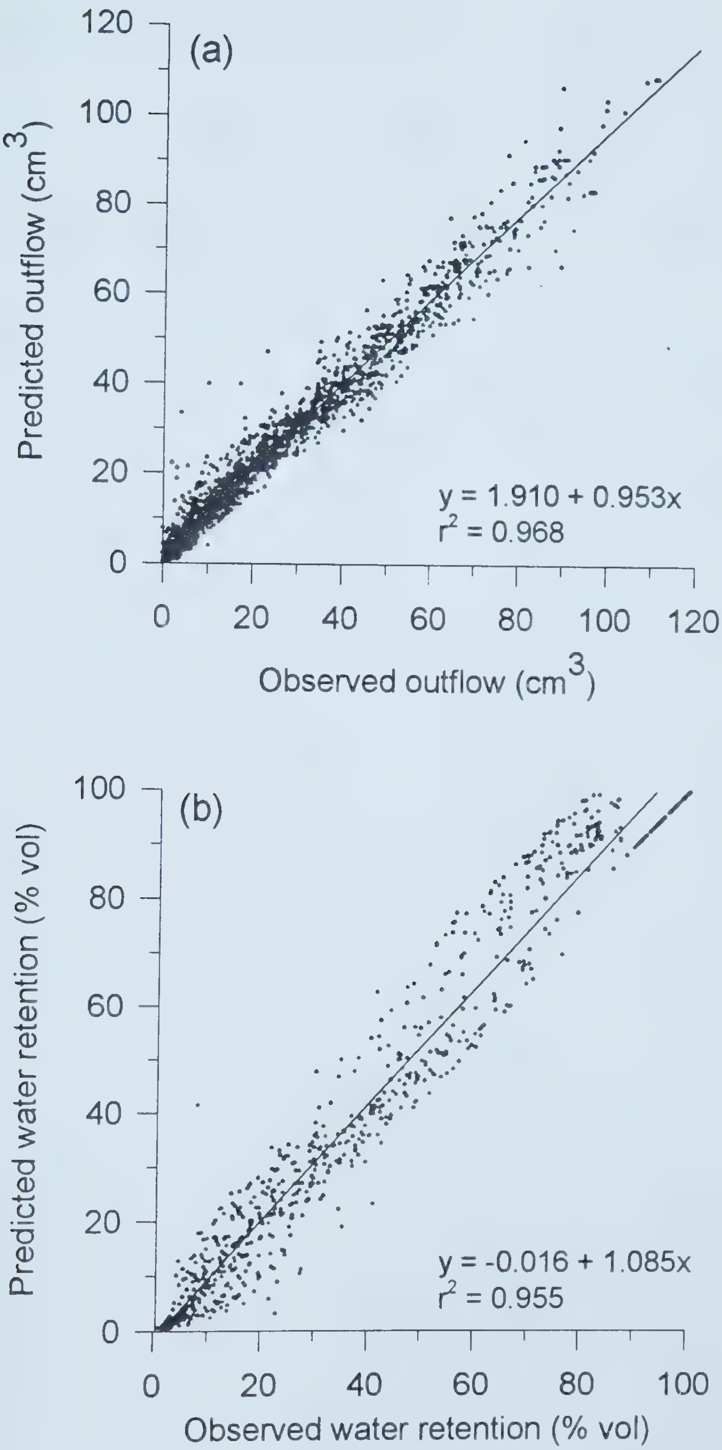

Table 6-3 Mean square residuals and r^2 from regressions of observed vs predicted transient outflow $Q(t)$, and water retention $\theta(h)$ for three different optimization approaches.

	Approach 1		Approach 2		Approach 3	
	MS residual	r^2	MS residual	r^2	MS residual	r^2
$Q(t)$	11.217	0.977	53.932	0.903	15.994	0.968
$\theta(h)$	0.0154	0.866	0.0016	0.982	0.0049	0.955

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6.2 APPENDIX 2

Errors in estimation of hydrologic parameters

The inverse method for estimating soil hydraulic functions described in Chapter two was developed for rigid, porous media (van Dam et al. 1990). Therefore an assumption of the model is that soil volume remains constant during the outflow process. This assumption may not be valid for some organic, or clay soils which exhibit shrinkage or swelling with changes in water content. Errors in the estimation of hydrologic parameters caused by soil shrinkage result from loss of contact between the soil and pressure plate, and from errors in the determination of soil water content (Crescimanno and Iovino 1995).

The presence of macro-pores can create difficulties when using models based on Darcy's law, which assumes homogeneous and isotropic soil conditions (Bronswijk 1988). Heterogeneous soil macro-pores can result in preferential unsaturated flow through large pores that "short-circuit" uniform flow through the bulk soil (Bouma and Dekker 1978, Bouma 1983), or by the existence of large air-filled pores which act as barriers restricting unsaturated flow (Bouma 1983). These conditions can disrupt pore continuity through the pressure plate and soil sample which can isolate, or restrict water flow from regions of the sample during outflow experiments. However, by imposing small progressive pressure steps, multi-step outflow procedures result in more uniform changes in water potential and conductivity than in one-step procedures thereby providing better estimation of the mean hydrologic properties of the soil (van Dam *et al.* 1990). Furthermore, most of the preferential flow can be expected in the wetter range of soil water contents (Hopmans *et al.* 1992). In this study, the first pressure step (saturation to -5 cm head) was omitted to guard against this condition. Crescimanno and Iovino (1995) confirmed negligible loss of soil-plate contact by comparing soil water retention determined during outflow experiments with water retention determined independently. Though this was not done in the present study, the variability of water contents between replicate samples determined during outflow measurements (using Tempe cells) was similar to the variability of water contents observed using pressure plate apparatus. Furthermore, a discontinuity in the shape of water retention curves between -5 to -100 cm

head determined with Tempe cells, and -300 to -15000 cm head determined using pressure plate apparatus was not evident. This suggests that either uniform loss of soil-plate contact occurred using both methods, or that loss of soil-plate contact was negligible. Uniform loss of soil-plate contact using these two independent methods was unlikely, thus I assumed negligible loss of soil-plate contact occurred during outflow experiments.

Errors caused by evaporation from collection flasks were examined by comparing water contents at -100 cm head determined by oven drying with water contents determined by subtracting outflow volumes from saturation water contents. Results of this comparison is presented in Figure 6-4. Peat water contents determined from outflow volume very slightly underestimated water contents based on oven drying over the range of water contents observed. Mean differences between water contents determined from outflow and oven drying were less than 0.0014 θv. Based on these results, I concluded that evaporation from collection flasks during outflow was also negligible.

Errors in estimation of hydrologic parameters due to shrinkage were examined by calculating the effect of shrinkage on determination of soil water content (Crescimanno and Iovino 1995). As samples were not removed from Tempe cells after equilibrium with each pressure step, estimates of sample volume were not available after each pressure step. The effect of shrinkage on water content was determined after equilibrium was reached at the final pressure step of 100 cm head (Table 6-4). Mean volume loss from saturation to -100 cm head was -4.5% for drained peat, and -6.5% in undrained peat. The difference between saturated volume, and volume at 100 cm head was significant for both drainage conditions and depths ($p<0.05$), except for drained peat at 0-10 cm ($p=0.24$), and 20-30 cm ($p=0.06$) depths. Shrinkage was not uniform in the vertical and horizontal planes. Mean shrinkage of drained peat was -0.17 cm in the vertical plane compared to -0.01 cm in the horizontal plane, while undrained peat lost -0.20 cm and -0.07 cm for the same dimensions, respectively. However, errors in estimation of water content were smaller than those of relative volume loss. Based on actual sample volumes at 100 cm head, the calculation of water content on a saturated volume basis resulted in underestimation of actual water content by 2.58% θv and 2.42% θv, for drained and undrained peat respectively. This error was considerably smaller than the variation between replicate samples of drainage and depth

conditions observed at Saulteaux River. Based on this criterion (Crescimanno and Iovino 1995), I concluded that sample shrinkage during outflow also had a negligible effect on the estimation of hydrologic parameters using the inverse method.

Figure 6-4 The relationship between peat water content at -100 cm head determined by oven drying and water content based on outflow volume from Tempe cells.

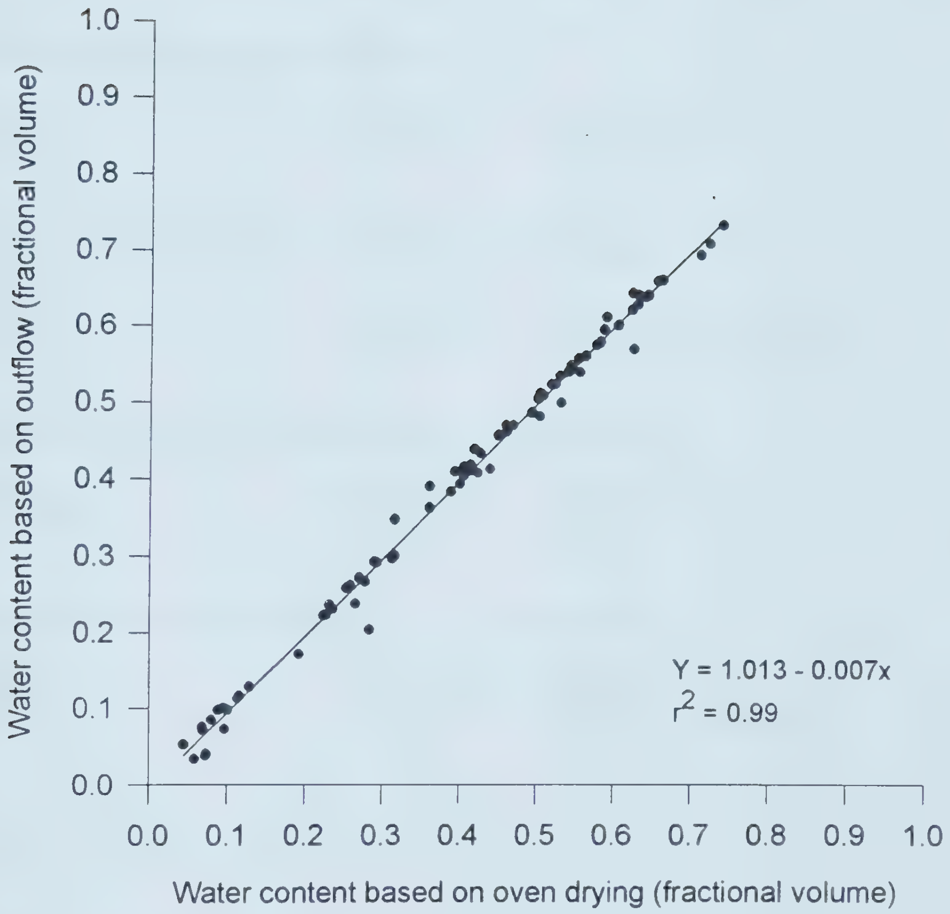

Table 6-4 Linear and volume shrinkage, and calculated underestimation of water content at -100 cm head of drained and undrained peat for four depth increments. Values in brackets indicate one standard error of the mean.

	Depth Increment (cm)			
	0-10	10-20	20-30	30-40
Vertical shrinkage (cm) from saturation to 100 cm				
Drained	-0.09 (0.05)	-0.16 (0.02)	-0.14 (0.04)	-0.18 (0.05)
Undrained	-0.14 (0.04)	-0.14 (0.03)	-0.17 (0.03)	-0.19 (0.02)
Horizontal shrinkage (cm) from saturation to 100 cm head				
Drained	0.00 (0.05)	-0.03 (0.05)	-0.02 (0.08)	-0.04 (0.05)
Undrained	-0.02 (0.06)	-0.04 (0.07)	-0.02 (0.03)	-0.01 (0.06)
Total volume shrinkage (%) from saturation to 100 cm head				
Drained	-2.45 (1.91)	-3.88 (0.84)	-3.93 (1.92)	-3.84 (1.43)
Undrained	-4.21 (0.73)	-4.47 (0.94)	-4.91 (0.51)	-4.76 (0.85)
Underestimation of actual water content at 100 cm head due to shrinkage (% θv)				
Drained	-0.85 (0.58)	-3.06 (0.94)	-3.73 (1.60)	-2.68 (1.04)
Undrained	-0.33 (0.08)	-1.03 (0.30)	-3.37 (0.92)	-4.84 (1.17)

6.2.1 Literature cited

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6.3 APPENDIX 3

Peat properties at Wolf Creek

Frozen peat cores were extracted from drained (30-m spacing) and undrained areas of Wolf Creek with a chain-saw during the winter of 1991-1992. Sampling methods and plot selection criteria were identical as those described for Saulteaux River in Chapter 2. Selected physical and chemical properties in drained and undrained areas of Wolf Creek were determined from these cores using methods detailed in Chapter 2. Results of these measurements are presented in Table 6-5.

Table 6-5 Mean peat properties of drained and undrained areas at Wolf Creek for four depth increments. Values in brackets indicate 1 standard error (n=5).

	Depth Increment			
	0-10 cm	10-20 cm	20-30 cm	30-40 cm
pH ($CaCl_2$)				
Drained	4.60 (0.104)	4.34 (0.064)	4.48 (0.024)	4.62 (0.014)
Undrained	4.58 (0.383)	4.84 (0.182)	4.60 (0.060)	4.52 (0.031)
% Ash				
Drained	10.32 (1.18)	7.07 (0.35)	7.57 (0.81)	8.70 (0.62)
Undrained	6.22 (1.05)	9.63 (1.42)	6.67 (0.23)	6.65 (0.28)
Particle Density (g cm^{-3})				
Drained	1.516 (0.025)	1.502 (0.005)	1.501 (0.008)	1.510 (0.008)
Undrained	1.723 (0.090)	1.681 (0.050)	1.597 (0.041)	1.558 (0.023)
% Rubbed Fibre				
Drained	45.87 (3.13)	38.14 (2.76)	32.16 (3.48)	28.87 (0.67)
Undrained	82.31 (2.61)	72.13 (5.43)	57.87 (4.81)	46.83 (6.61)
% R Factor				
Drained	39.99 (3.69)	43.24 (6.87)	48.89 (4.89)	55.51 (3.66)
Undrained	20.92 (1.94)	26.38 (1.72)	33.01 (2.43)	41.36 (2.23)

6.4 APPENDIX 4

Analysis of variance; model descriptions and results for Chapter Three.

Analysis of variance was performed on results from measurement of soil properties (water content, bulk density, solid volume fraction, and air filled porosity), aeration (O_2 concentration, oxygen flux density, ODR, and aerobic limit depth), and water table levels at both peatlands. A randomized split-plot design was used to examine yearly (1991 and 1992), drainage (drained and undrained), and soil depth effects (0-10, 10-20, 20-30, and 30-40 cm depth) for these variables with the exception of aerobic limit, and water table depth which had no fixed depth factor.

Though the study was conducted during two summer seasons, a complete model (including a factor for year) was not possible for ODR and aerobic limit depth as these were measured during 1992 only. For this reason, and as significant differences between years were evident with many variables, separate analyses were conducted for each year individually to simplify explanation of results. The generalized full, and individual year ANOVA models are presented in Table 6-6. Deviations from these generalized models were as follows:

1) The full model was not used with ODR and aerobic limit data (measured in 1992 only).

2) Models for aerobic limit and water table data did not contain a fixed factor for depth. Monthly measurements were included as random factors in analysis of these variables.

3) Repeated measures ANOVA was used for O_2 concentration data.

4) Saulteaux River peatland was measured four times during 1992

5) The number of levels for depth were modified to balance data for soil properties and from "Raney" probe measurements. Only two levels were used for Wolf Creek in 1991, four levels were used at Wolf Creek in 1992, and three levels were included at Saulteaux River during both 1991 and 1992.

Though monthly measurements were considered random observations of drainage and depth effects, all fixed effects were tested against their interaction with the random factor "plot" (Table 6-7). The results of F tests for fixed factors from full and individual years models ANOVA's are summarized in Tables 6-8, 6-9, 6-10, and 6-11.

Table 6-6 Generalized full, and individual year ANOVA models used in analysis of soil properties, aeration, and water table data at Saulteaux River and Wolf Creek.

Factor	Subscript	Levels	Type
Block (B)	*i*	5	Random
Year (A)	*j*	2	Fixed
Drainage (D)	*k*	2	Fixed
Depth (E)	*l*	4	Fixed
Month (M)	*m*	3	Random

Full model:

$$Y_{ijklm} = \mu + B_i + Y_j + BY_{ij} + D_k + BD_{ik} + AD_{jk} + BAD_{ijk} + E_l + BE_{il} + AE_{jl} + BAE_{ijl} + DE_{kl} + BDE_{ikl} + ADE_{jkl} + BADE_{ijkl} + M_{m(ijkl)}$$

Individual year model:

$$Y_{iklm} = \mu + B_i + D_k + BD_{ik} + E_l + BE_{il} + DE_{kl} + BDE_{ikl} + M_{m(ikl)}$$

Table 6-7 Expected mean squares (EMS) for generalized full and individual year ANOVA models.

Factor	Full model EMS	Individual year model EMS
B_i	$\sigma^2 + 48\,\sigma^2_B$	$\sigma^2 + 24\,\sigma^2_B$
A_j	$\sigma^2 + 24\,\sigma^2_{BA} + 120\,\sigma^2_A$	
BA_{ij}	$\sigma^2 + 24\,\sigma^2_{BA}$	
D_k	$\sigma^2 + 24\,\sigma^2_{BD} + 12\,\sigma^2_D$	$\sigma^2 + 12\,\sigma^2_{BD} + 6\,\sigma^2_D$
BD_{ik}	$\sigma^2 + 24\,\sigma^2_{BD}$	$\sigma^2 + 12\,\sigma^2_{BD}$
AD_{jk}	$\sigma^2 + 12\,\sigma^2_{BAD} + 60\,\sigma^2_{AD}$	
BAD_{ijk}	$\sigma^2 + 12\,\sigma^2_{BAD}$	
E_l	$\sigma^2 + 12\,\sigma^2_{BE} + 60\,\sigma^2_E$	$\sigma^2 + 6\,\sigma^2_{BE} + 30\,\sigma^2_E$
BE_{ij}	$\sigma^2 + 12\,\sigma^2_{BE}$	$\sigma^2 + 6\,\sigma^2_{BE}$
AE_{jl}	$\sigma^2 + 6\,\sigma^2_{BAE} + 30\,\sigma^2_{AE}$	
BAE_{ijl}	$\sigma^2 + 6\,\sigma^2_{BAE}$	
DE_{kl}	$\sigma^2 + 6\,\sigma^2_{BDE} + 30\,\sigma^2_{DE}$	$\sigma^2 + 3\,\sigma^2_{BDE} + 15\,\sigma^2_{DE}$
BDE_{ikl}	$\sigma^2 + 6\,\sigma^2_{BDE}$	$\sigma^2 + 3\,\sigma^2_{BDE}$
ADE_{jkl}	$\sigma^2 + 3\,\sigma^2_{BADE} + 15\,\sigma^2_{ADE}$	
$BADE_{ijkl}$	$\sigma^2 + 3\,\sigma^2_{BADE}$	
$M_{m(ikl)}$		σ^2
$M_{m(ijkl)}$	σ^2	

Table 6-8 Results of ANOVA's of soil properties and aeration measurements at Saulteaux River and Wolf Creek using the full model. Values indicate P>F.

Saulteaux River

Depths evaluated	0-30 cm	0-30 cm	0-30 cm
Variable	Water content	Bulk density	Solid volume
Year	0.057	0.386	0.315
Drainage	0.116	<0.001	<0.001
Year*Drainage	0.761	0.501	0.732
Depth	<0.001	<0.001	<0.001
Year*Depth	0.348	0.787	0.588
Drainage*Depth	0.934	0.640	0.931
Year*Drainage*Depth	0.935	0.235	0.352

Depths evaluated	0-30 cm	0-40 cm	0-30 cm
Variable	Air filled porosity	O_2 concentration	Oxygen flux density
Year	0.066	0.328	0.234
Drainage	0.052	0.011	0.481
Year*Drainage	0.814	0.597	0.001
Depth	<0.001	<0.001	<0.001
Year*Depth	0.409	0.065	0.093
Drainage*Depth	0 956	0.009	0.029
Year*Drainage*Depth	0.989	0.273	0.267

Wolf Creek

Depths evaluated	0-20 cm	0-20 cm	0-20 cm
Variable	Water content	Bulk density	Solid volume
Year	0.003	0.280	0.284
Drainage	0.153	<0.001	<0.001
Year*Drainage	0.658	0.460	0.450
Depth	<0.001	0.002	0.002
Year*Depth	0.111	0.128	0.144
Drainage*Depth	0.609	0.011	0.008
Year*Drainage*Depth	0.008	0.710	0.764

Depths evaluated	0-20 cm	0-40 cm	0-20 cm
Variable	Air filled porosity	O_2 concentration	Oxygen flux density
Year	0.004	0.022	0.003
Drainage	0.056	0.034	0.008
Year*Drainage	0.630	0.587	0.098
Depth	<0.001	<0.001	0.001
Year*Depth	0.149	0.045	0.335
Drainage*Depth	0.902	0.124	0.167
Year*Drainage*Depth	0.124	0.127	0.783

Table 6-9 Results of ANOVA's of soil properties and aeration measurements at Saulteaux River using the individual year model for 1991 and 1992. Values indicate P>F.

Saulteaux River - 1991

Depths evaluated	0-30 cm	0-30 cm	0-30 cm
Variable	Water content	Bulk density	Solid volume
Drainage	0.027	<0.001	<0.001
Depth	<0.001	<0.001	<0.001
Drainage*Depth	0.724	0.559	0.845

Depths evaluated	0-30 cm	0-40 cm	0-30 cm
Variable	Air filled porosity	O_2 concentration	Oxygen flux density
Drainage	0.005	0.028	0.141
Depth	<0.001	<0.001	<0.001
Drainage*Depth	0.824	0.014	0.171

Saulteaux River - 1992

Depths evaluated	0-30 cm	0-30 cm	0-30 cm
Variable	Water content	Bulk density	Solid volume
Drainage	0.222	<0.001	<0.001
Depth	<0.001	<0.001	<0.001
Drainage*Depth	0.792	0.410	0.194

Depths evaluated	0-30 cm	0-40 cm	0-30 cm
Variable	Air filled porosity	O_2 concentration	Oxygen flux density
Drainage	0.129	0.008	0.914
Depth	<0.001	<0.001	<0.001
Drainage*Depth	0.796	0.068	0.040

Depths evaluated	0-40 cm
Variable	ODR
Drainage	0.040
Depth	0.001
Drainage*Depth	0.006

Table 6-10 Results of ANOVA's of soil properties and aeration data from Wolf Creek using the individual year model for 1991 and 1992. Values indicate P>F.

Wolf Creek - 1991

Depths evaluated	0-20 cm	0-20 cm	0-20 cm
Variable	Water content	Bulk density	Solid volume
Drainage	0.029	<0.001	<0.001
Depth	0.001	0.028	0.026
Drainage*Depth	0.403	0.229	0.230

Depths evaluated	0-20 cm	0-40 cm	0-20 cm
Variable	Air filled porosity	O_2 concentration	Oxygen flux density
Drainage	0.009	0.329	0.014
Depth	0.001	<0.001	0.003
Drainage*Depth	0.739	0.154	0.613

Wolf Creek - 1992

Depths evaluated	0-40 cm	0-40 cm	0-40 cm
Variable	Water content	Bulk density	Solid volume
Drainage	0.324	0.007	0.004
Depth	<0.001	<0.001	<0.001
Drainage*Depth	0.202	0.003	0.001

Depths evaluated	0-40 cm	0-40 cm	0-40 cm
Variable	Air filled porosity	O_2 concentration	Oxygen flux density
Drainage	0.168	0.035	0.004
Depth	<0.001	<0.001	<0.001
Drainage*Depth	0.100	0.102	0.220

Depths evaluated	0-40 cm
Variable	ODR
Drainage	0.071
Depth	<0.001
Drainage*Depth	0.009

Table 6-11 Results of ANOVA's of water table level and aerobic limit depth measurements at Wolf Creek and Saulteaux River using the full and individual year models. Monthly measurements were included as random factors in the models. Values indicate P>F.

Full Model ANOVA

Variable	Saulteaux River Water table	Wolf Creek Water table
Year	0.545	<0.001
Month(Year)	<0.001	<0.001
Drainage	0.011	<0.001
Year*Drainage	0.861	0.080
Month(Year)*Drainage	0.0261	0.001

Individual Year Model ANOVA

Saulteaux River

Variable	1991 Water table level	1992 Water table level	1992 Aerobic limit depth
Month	0.047	<0.001	<0.001
Drainage	0.009	0.016	0.049
Month*Drainage	0.331	0.009	0.001

Wolf Creek

Variable	1991 Water table level	1992 Water table level	1992 Aerobic limit depth
Month	<0.001	<0.001	0.029
Drainage	0.001	<0.001	0.006
Month*Drainage	0.003	0.026	0.384

6.5 APPENDIX 5

Mean values for monthly measurements of soil moisture and aeration at Saulteaux River and Wolf Creek.

Table 6-12 Mean soil water content, air filled porosity, oxygen concentration, oxygen diffusion rate (ODR), oxygen flux, and relative diffusivity for four depths; and water table levels, and aerobic limit depths for drained and undrained areas of Saulteaux River on three sampling dates in 1991. Values in brackets indicate one standard error.

	July 29		September 10		October 15	
	Drained	Undrained	Drained	Undrained	Drained	Undrained
Depth increment (cm)						
	Soil water content (fractional volume)					
0-10	0.32 (0.07)	0.17 (0.04)	0.30 (0.04)	0.33 (0.06)	0.43 (0.04)	0.21 (0.03)
10-20	0.59 (0.08)	0.59 (0.05)	0.60 (0.04)	0.47 (0.02)	0.69 (0.04)	0.61 (0.11)
20-30	0.78 (0.05)	--- ---	0.78 (0.03)	--- ---	0.78 (0.04)	0.81 (0.12)
30-40	0.84 (0.04)	--- ---	0.75 (0.02)	--- ---	0.84 (0.02)	--- ---
	Air filled porosity (fractional volume)					
0-10	0.61 (0.06)	0.82 (0.03)	0.64 (0.05)	0.64 (0.06)	0.49 (0.04)	0.77 (0.03)
10-20	0.34 (0.08)	0.35 (0.06)	0.31 (0.05)	0.53 (0.01)	0.21 (0.05)	0.34 (0.12)
20-30	0.14 (0.07)	--- ---	0.12 (0.04)	--- ---	0.12 (0.04)	0.14 (0.08)
30-40	0.06 (0.05)	--- ---	0.14 (0.03)	--- ---	0.04 (0.01)	--- ---
	Oxygen concentration (%)					
0-10	20.51 (0.16)	20.22 (0.08)	20.70 (0.04)	20.70 (0.04)	18.48 (2.16)	20.65 (0.05)
10-20	19.22 (0.44)	17.47 (2.24)	20.49 (0.10)	14.96 (2.85)	18.01 (2.51)	12.78 (1.28)
20-30	12.57 (3.77)	9.59 (0.79)	16.88 (2.87)	9.17 (1.48)	18.35 (1.34)	13.45 (0.49)
30-40	8.90 (0.93)	8.30 (0.70)	10.85 (2.32)	8.84 (0.45)	13.87 (0.45)	12.27 (1.27)
	Oxygen diffusion rate (x 10^{-8} g cm^{-2} min^{-1})					
0-10	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---
10-20	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---
20-30	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---
30-40	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---
	Oxygen flux (µg cm^{-2} min^{-1})					
0-10	195.6 (13.86)	182.9 (24.22)	163.3 (18.67)	80.7 (32.44)	141.7 (23.55)	132.2 (17.08)
10-20	94.7 (19.46)	86.3 (13.59)	115.6 (33.43)	126.1 (2.00)	139.5 (17.27)	62.5 (57.24)
20-30	67.4 (18.53)	--- ---	40.9 (9.72)	--- ---	65.4 (18.77)	10.4 (2.23)
30-40	63.9 (8.67)	--- ---	18.0 (4.45)	--- ---	16.9 (3.90)	--- ---
	Relative diffusivity (D/Do)					
0-10	0.63 (0.08)	0.68 (0.14)	0.48 (0.07)	0.27 (0.13)	0.47 (0.10)	0.45 (0.05)
10-20	0.25 (0.07)	0.20 (0.05)	0.34 (0.11)	0.50 (0.02)	0.43 (0.07)	0.18 (0.14)
20-30	0.19 (0.04)	--- ---	0.12 (0.02)	--- ---	0.19 (0.05)	0.08 (0.06)
30-40	0.28 (0.06)	--- ---	0.11 (0.07)	--- ---	0.06 (0.02)	--- ---
	Water table level (cm)					
	66.20 (8.53)	25.30 (1.59)	60.50 (8.28)	19.70 (2.87)	59.70 (7.63)	24.20 (3.01)
	Aerobic limit depth (cm)					
	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---

Table 6-13 Mean soil water content, air filled porosity, oxygen concentration, oxygen diffusion rate (ODR), oxygen flux, and relative diffusivity for four depths; and water table levels, and aerobic limit depths for drained and undrained areas of Saulteaux River on four sampling dates in 1992. Values in brackets indicate one standard error.

	June 16		July 31		August 25		September 23	
	Drained	Undrained	Drained	Undrained	Drained	Undrained	Drained	Undrained
Depth increment (cm)								
	Soil water content (fractional volume)							
0-10	0.37 (0.11)	0.34 (0.03)	0.31 (0.06)	0.18 (0.03)	0.25 (0.06)	0.07 (0.02)	0.35 (0.04)	0.23 (0.06)
10-20	0.55 (0.06)	0.52(0.05)	0.58 (0.08)	0.58 (0.05)	0.60 (0.07)	0.21 (0.04)	0.55 (0.07)	0.60 (0.08)
20-30	0.79 (0.02)	--- ---	0.77 (0.08)	--- ---	0.61 (0.08)	0.56 (0.05)	0.70 (0.04)	0.73 (0.09)
30-40	0.80 (0.02)	--- ---	0.82 (0.05)	--- ---	0.67 (0.11)	--- ---	0.79 (0.01)	--- ---
	Air filled porosity (fractional volume)							
0-10	0.56 (0.11)	0.64 (0.03)	0.63 (0.06)	0.81 (0.03)	0.69 (0.06)	0.91 (0.02)	0.58 (0.04)	0.74 (0.06)
10-20	0.37 (0.06)	0.44 (0.03)	0.35 (0.09)	0.36 (0.06)	0.32 (0.08)	0.77 (0.05)	0.37 (0.07)	0.33 (0.08)
20-30	0.10 (0.02)	--- ---	0.13 (0.08)	--- ---	0.30 (0.09)	0.39 (0.06)	0.20 (0.05)	0.19 (0.08)
30-40	0.10 (0.02)	--- ---	0.07 (0.06)	--- ---	0.23 (0.12)	--- ---	0.10 (0.01)	--- ---
	Oxygen concentration (%)							
0-10	20.53 (0.16)	17.26 (1.57)	20.36 (0.17)	20.53 (0.07)	20.61 (0.05)	20.65 (0.05)	20.61 (0.05)	20.74 (0.00)
10-20	16.76 (1.90)	16.09 (1.04)	19.40 (0.38)	16.84 (2.86)	19.82 (0.37)	19.73 (0.36)	19.98 (0.29)	14.83 (2.35)
20-30	14.83 (1.52)	17.18 (0.28)	13.83 (3.32)	5.36 (1.29)	17.09 (1.52)	12.44 (2.39)	18.98 (0.63)	10.81 (0.36)
30-40	16.13 (1.10)	17.30 (0.52)	10.93 (2.16)	9.93 (1.74)	11.69 (2.59)	10.14 (1.20)	16.59 (0.89)	10.77 (0.84)
	Oxygen diffusion rate (x 10^{-8} g cm^{-2} min^{-1})							
0-10	--- ---	--- ---	4.04 (0.64)	3.83 (1.43)	2.25 (0.35)	2.79 (0.47)	2.54 (0.61)	6.94 (2.45)
10-20	--- ---	--- ---	3.26 (0.93)	0.30 (0.17)	4.19 (0.39)	2.17 (0.66)	3.63 (0.47)	1.33 (0.76)
20-30	--- ---	--- ---	2.31 (0.90)	0.16 (0.07)	1.96 (0.57)	1.36 (0.60)	2.86 (0.69)	0.19 (0.01)
30-40	--- ---	--- ---	1.73 (0.74)	0.09 (0.02)	2.48 (1.01)	0.48 (0.15)	2.35 (0.73)	0.30 (0.16)
	Oxygen flux (μg cm^{-2} min^{-1})							
0-10	127.7 (26.8)	155.7 (38.2)	192.7 (11.3)	183.9 (25.5)	159.4 (25.5)	233.1 (6.2)	156.2 (17.8)	200.3 (17.3)
10-20	62.8 (44.0)	13.3 (12.1)	96.7 (20.5)	88.6 (12.6)	112.7 (9.9)	159.0 (16.7)	125.3 (25.0)	36.1 (22.4)
20-30	17.2 (12.0)	--- ---	65.3 (20.0)	--- ---	74.9 (12.7)	62.7 (15.4)	95.6 (32.9)	10.3 (9.3)
30-40	6.9 (1.7)	--- ---	64.3 (8.0)	--- ---	38.1 (11.7)	--- ---	34.0 (11.5)	--- ---
	Relative diffusivity (D/Do)							
0-10	0.41 (0.10)	0.43 (0.13)	0.64 (0.07)	0.67 (0.13)	0.48 (0.08)	0.78 (0.04)	0.49 (0.09)	0.70 (0.09)
10-20	0.20 (0.12)	0.29 (0.09)	0.21 (0.04)	0.21 (0.02)	0.31 (0.03)	0.50 (0.07)	0.37 (0.09)	0.11 (0.07)
20-30	0.08 (0.02)	--- ---	0.15 (0.02)	--- ---	0.25 (0.06)	0.22 (0.03)	0.30 (0.11)	0.04 (0.05)
30-40	0.03 (0.01)	--- ---	0.19 (0.16)	--- ---	0.09 (0.02)	--- ---	0.09 (0.04)	--- ---
	Water table level (cm)							
	40.70 (9.96)	13.40 (1.66)	67.00 (9.17)	26.40 (1.91)	79.60 (8.49)	36.20 (3.12)	71.10 (11.9)	22.50 (2.73)
	Aerobic limit depth (cm)							
	22.10 (5.14)	15.80 (2.33)	44.80 (7.23)	22.00 (1.18)	57.90 (8.11)	29.80 (3.57)	52.40 (7.61)	22.80 (1.59)

Table 6-14 Mean soil water contents air filled porosity, oxygen concentration, oxygen diffusion rate (ODR), oxygen flux, and relative diffusivity for four depths; and water table levels, and aerobic limit depths for drained and undrained areas of Wolf Creek on three sampling dates in 1991. Values in brackets indicate one standard error.

	August 2		August 20		September 12	
	Drained	Undrained	Drained	Undrained	Drained	Undrained
Depth increment (cm)						
	Soil water content (fractional volume)					
0-10	0.33 (0.04)	0.28 (0.03)	0.35 (0.06)	0.22 (0.01)	0.42 (0.04)	0.24 (0.03)
10-20	0.66 (0.05)	0.53 (0.03)	0.66 (0.05)	0.59 (0.05)	0.57 (0.04)	0.56 (0.08)
20-30	0.82 (0.02)	--- ---	0.77 (0.09)	--- ---	0.73 (0.05)	--- ---
30-40	0.82 (0.05)	--- ---	--- ---	--- ---	0.83 (0.03)	--- ---
	Air filled porosity (fractional volume)					
0-10	0.62 (0.05)	0.70 (0.03)	0.61 (0.07)	0.76 (0.01)	0.51 (0.04)	0.75 (0.03)
10-20	0.25 (0.06)	0.46 (0.05)	0.26 (0.05)	0.39 (0.04)	0.36 (0.05)	0.42 (0.05)
20-30	0.07 (0.03)	--- ---	0.12 (0.11)	--- ---	0.18 (0.06)	--- ---
30-40	0.07 (0.05)	--- ---	--- ---	--- ---	0.06 (0.04)	--- ---
	Oxygen concentration (%)					
0-10	20.36 (0.23)	16.86 (2.37)	19.90 (0.39)	18.38 (2.02)	20.65 (0.08)	16.67 (1.68)
10-20	15.79 (2.87)	13.93 (1.25)	15.76 (3.54)	13.30 (0.88)	18.68 (1.09)	12.27 (1.01)
20-30	13.87 (2.57)	13.93 (0.90)	13.35 (2.63)	14.72 (0.58)	15.17 (2.55)	11.60 (1.47)
30-40	9.76 (2.31)	13.88 (1.69)	10.74 (2.23)	12.10 (2.39)	9.55 (2.62)	9.55 (1.47)
	Oxygen diffusion rate ($\times 10^{-8}$ g cm^{-2} min^{-1})					
0-10	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---
10-20	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---
20-30	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---
30-40	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---
	Oxygen flux (μg cm^{-2} min^{-1})					
0-10	182.4 (13.3)	88.0 (23.6)	128.4 (12.1)	54.9 (4.7)	153.8 (7.4)	126.8 (39.1)
10-20	70.7 (10.6)	55.6 (15.3)	55.8 (23.5)	31.5 (18.2)	78.4 (22.2)	28.5 (6.9)
20-30	60.1 (7.6)	--- ---	40.8 (20.4)	--- ---	24.5 (10.6)	--- ---
30-40	45.9 (3.9)	--- ---	--- ---	--- ---	15.3 (10.2)	--- ---
	Relative diffusivity (D/Do)					
0-10	0.60 (0.07)	0.31 (0.12)	0.38 (0.05)	0.13 (0.02)	0.44 (0.03)	0.43 (0.14)
10-20	0.30 (0.08)	0.19 (0.07)	0.22 (0.09)	0.16 (0.03)	0.22 (0.06)	0.12 (0.04)
20-30	0.18 (0.02)	--- ---	0.16 (0.02)	--- ---	0.11 (0.04)	--- ---
30-40	0.18 (0.03)	--- ---	--- ---	--- ---	0.11 (0.06)	--- ---
	Water table level (cm)					
	46.50 (3.98)	11.63 (2.19)	25.63 (1.55)	10.50 (0.65)	42.50 (3.57)	12.80 (0.37)
	Aerobic limit depth (cm)					
	--- ---	--- ---	--- ---	--- ---	--- ---	--- ---

Table 6-15 Mean soil water content, air filled porosity, oxygen concentration, oxygen diffusion rate (ODR), oxygen flux, and relative diffusivity for four depths; and water table levels, and aerobic limit depths for drained and undrained areas of Wolf Creek on three sampling dates in 1992. Values in brackets indicate one standard error.

	August 3		August 30		October 2	
	Drained	Undrained	Drained	Undrained	Drained	Undrained
Depth increment (cm)						
	Soil water content (fractional volume)					
0-10	0.16 (0.06)	0.17 (0.03)	0.18 (0.04)	0.11 (0.02)	0.23 (0.03)	0.18 (0.03)
10-20	0.45 (0.08)	0.39 (0.06)	0.35 (0.03)	0.27 (0.07)	0.49 (0.08)	0.45 (0.03)
20-30	0.67 (0.05)	0.59 (0.07)	0.67 (0.03)	0.53 (0.06)	0.74 (0.02)	0.69 (0.04)
30-40	0.82 (0.02)	--- ---	0.75 (0.02)	0.76 (0.04)	0.79 (0.02)	--- ---
	Air filled porosity (fractional volume)					
0-10	0.79 (0.07)	0.82 (0.03)	0.78 (0.04)	0.89 (0.02)	0.72 (0.03)	0.81 (0.03)
10-20	0.48 (0.09)	0.58 (0.06)	0.58 (0.03)	0.70 (0.08)	0.43 (0.08)	0.51 (0.03)
20-30	0.22 (0.06)	0.37 (0.08)	0.23 (0.03)	0.42 (0.07)	0.15 (0.03)	0.26 (0.04)
30-40	0.06 (0.02)	--- ---	0.14 (0.03)	0.16 (0.05)	0.09 (0.02)	--- ---
	Oxygen concentration (%)					
0-10	20.49 (0.12)	20.53 (0.21)	20.70 (0.04)	20.65 (0.05)	20.74 (0.00)	20.44 (0.13)
10-20	20.40 (0.08)	14.51 (3.21)	20.61 (0.05)	17.47 (2.64)	20.53 (0.07)	17.34 (2.01)
20-30	15.00 (3.18)	6.39 (1.41)	17.72 (0.88)	15.58 (1.82)	18.43 (0.75)	9.89 (1.03)
30-40	8.97 (1.10)	9.53 (1.43)	12.86 (2.70)	8.97 (1.02)	12.95 (2.28)	11.56 (0.33)
	Oxygen diffusion rate (x 10^{-8} g cm^{-2} min^{-1})					
0-10	3.50 (0.84)	5.25 (0.94)	2.17 (0.61)	2.85 (0.56)	6.64 (0.50)	7.32 (0.26)
10-20	3.74 (1.05)	1.47 (1.00)	3.84 (0.26)	3.92 (0.69)	4.52 (1.07)	3.93 (0.30)
20-30	1.79 (0.78)	0.32 (0.15)	2.28 (0.56)	0.82 (0.42)	2.49 (0.88)	1.00 (0.65)
30-40	1.22 (0.69)	0.18 (0.06)	0.40 (0.09)	0.21 (0.04)	0.59 (0.30)	0.50 (0.28)
	Oxygen flux (μg cm^{-2} min^{-1})					
0-10	217.8 (12.0)	179.7 (16.3)	209.1 (12.2)	203.7 (10.6)	219.9 (7.6)	178.4 (18.7)
10-20	149.8 (27.4)	91.9 (7.7)	169.0 (24.3)	161.6 (24.4)	125.7 (27.6)	37.9 (18.2)
20-30	87.1 (14.0)	52.5 (6.4)	67.4 (17.3)	36.9 (8.2)	35.2 (13.2)	12.9 (4.5)
30-40	85.4 (10.1)	--- ---	40.0 (15.8)	20.6 (2.1)	14.4 (4.1)	--- ---
	Relative diffusivity (D/Do)					
0-10	0.75 (0.05)	0.63 (0.05)	0.68 (0.06)	0.72 (0.06)	0.68 (0.03)	0.52 (0.07)
10-20	0.51 (0.12)	0.31 (0.02)	0.51 (0.09)	0.53 (0.09)	0.39 (0.08)	0.11 (0.04)
20-30	0.27 (0.07)	0.26 (0.04)	0.21 (0.06)	0.19 (0.08)	0.10 (0.05)	0.07 (0.02)
30-40	0.08 (0.09)	--- ---	0.07 (0.01)	0.12 (0.01)	0.07 (0.03)	--- ---
	Water table level (cm)					
	67.80 (3.30)	30.50 (1.76)	78.70 (3.75)	44.40 (1.67)	79.00 (2.76)	33.60 (1.80)
	Aerobic limit depth (cm)					
	27.90 (1.49)	23.38 (1.07)	41.80 (3.33)	31.60 (2.16)	39.60 (4.39)	25.50 (0.89)

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